The Study on the Effects of Cable Capacitance on the Behaviour of Triplen Harmonics Produced By Synchronous Generator

by

Faiz Izzat Mohamed Akhir

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A final report submitted in partial fulfilment of

the requirements for the

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CERTIFICATION OF APPROVAL

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Approved by,

(Ir Mohd Faris Bin Abdullah)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

SEPTEMBER 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

FAIZ IZZAT MOHAMED AKHIR

ABSTRACT

The heavy usage of electronics equipment today has increased the amount of harmonics flowing in power system. This can lead to power quality problems. Harmonic by definition is a component of a periodic wave having a frequency that is an integral multiple of the fundamental power line frequency. Harmonics get more complicated in three phase application. In three phase application, we have to deal not only with phase conductors, but also the neutral conductor, triplen harmonics and sequence harmonics. Triplen harmonics are the odd multiple of third harmonics (3^{rd}, 9^{th}, 15^{th}, etc.). Triplen harmonics currents are the major cause of heat because they add together in neutral conductor. The magnitude of triplen harmonics currents can approach twice of the phase currents. Neutral conductors were designed with the ampacity as the phase conductors and when triplen harmonics currents add at the neutral, it causes them to overheat. The effect of this has been known from previous published journals. In this project, the author wants to find whether cable capacitance will have the same effect as neutral conductor. Any two conductors separated by a distance can store a charge. So any two wires in a cable can store a charge. This is what we called cable capacitance. In the experiment, capacitor will be introduced at each phase wire (red phase, yellow phase and blue phase) to act as cable capacitance. The triplen harmonics currents will be measured at capacitor to see whether capacitor affect how triplen harmonics currents produced by single generator behave in a power system. After the data have been gathered, it will be used to model the circuit in PSCAD. The purpose of this is to find the right source to be used in PSCAD simulation. The author hope by the end of this project, the findings will help the industry to reduce or suppressed the amount of harmonics and also detect the harmonics present in the power system by using simulation.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Harmonic by definition is a component of a periodic wave having a frequency that is an integral multiple of the fundamental power line frequency. The heavy usage of electronics equipment today has increased the amount of harmonics flowing in power system. This can lead to power quality problems. Current increasing in power system is one of the major effects of power system harmonics. This is particularly the case for the third harmonic, which causes a sharp increase in the zero sequence current, and therefore increases the current in the neutral conductor. The odd multiple of third harmonic (3^{rd}, 9^{th}, 15^{th}, etc.), also known as triplen harmonics, are zero sequence currents. The magnitude of these currents on the 3 phases is additive in neutral unlike the positive and negative sequence currents. This can lead to very large currents circulating in the neutral which will increase the temperature. The triplen harmonics voltages and currents have different characteristics, such as how they flow in the power system, when different load is connected. Aside from load, cable capacitance also can be one of the candidates that can affect how triplen harmonics behave in a power system. In this project, the objective is to study whether cable capacitance has an effect on the behaviour of triplen harmonics in a power system.

1.2 Problem Statement

The flow of triplen harmonics in a power system vary with different load connected to the power supply; either it is a linear load or non-linear load. As the 3 phase power flow to the load through transmission system, triplen harmonics currents present also flow in the same path. The cable used to transmit electricity has a capacitance that can affect the fundamental currents. Does the triplen harmonics currents also affected by the cable capacitance? In this study, we will see whether the cable capacitance, which is the ability of two conductors separated by insulation to store charge, affects the properties of triplen harmonics in a power system.

.3 Project Objectives

The objectives of this project are listed as below:

- To study the effects of cable capacitance on the behaviour of triplen harmonics generated by synchronous generator under balanced load condition. The balanced load will include the resistive, inductive and capacitive loads.

1.4 Scope of Study

- Doing literature review on triplen harmonics by studying the past journals, articles, and thesis.
- Simulating the previous experiment by building a model and simulate using the PSCAD software. The objective is to find the models that give equal or close result to the previous experiment. The results are essential because the perfect model can be guide for the lab works.
- Doing a lab experiment to make sure that the result of modelling is in tally with the actual result.
- Doing analysis and discussion on the results.

CHAPTER 2

LITERATURE REVIEW

2.1 Triplen Harmonics

The problematic harmonics are the 3rd, 9th, 15th, etc., which are called triplen harmonics. Triplen harmonics are of particular concern because they are zero sequence harmonics, unlike the fundamental, which is positive sequence. Balanced triplen harmonics are zero sequence in nature because their phase quantity having same magnitude and phase angle. From this fact, investigation has shown that the magnitude of these currents on 3 phases are additive in neutral [1, 2]. This frequent happen in grounded-wye systems with current flowing on the neutral conductor and can cause that conductor to overheat. Circulating currents in the neutral of the electric power system only can be caused by third harmonic voltage [3]. In each of 3 phases, there exists an equal third harmonic voltage. The different between fundamental voltage frequency and third harmonic is that is the degrees displacement. While fundamental frequency displaced by 120 electrical degrees, the third harmonic voltages is displaced by $3 \times 120 = 360$ degrees.

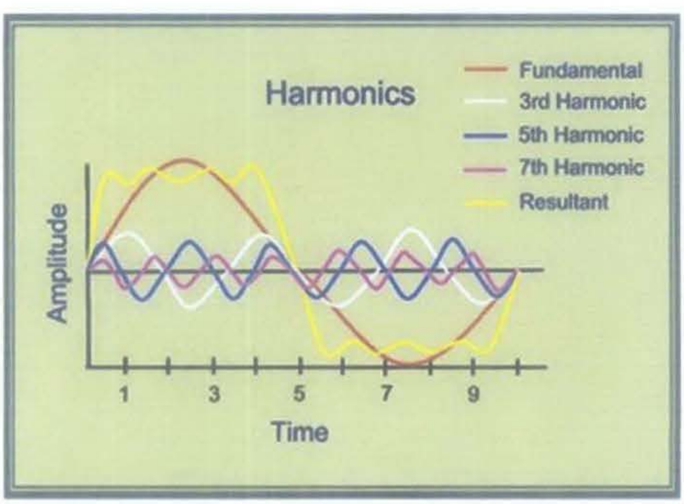

Figure 1: The resultant harmonics waveform due to fundamental, 3rd, 5th, and 7th harmonic.

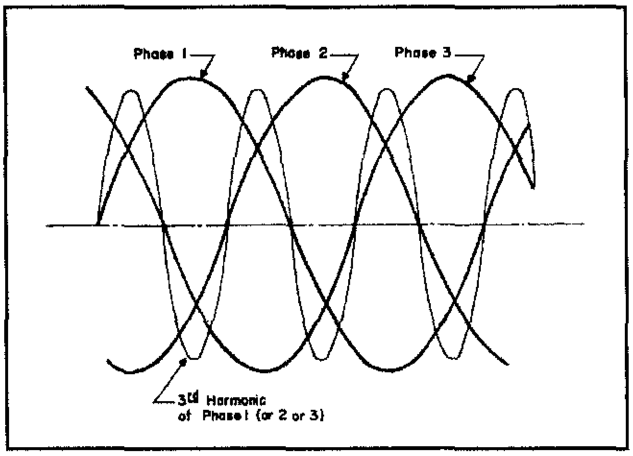

Figure 2: Fundamental and third harmonic voltage waveforms on a 3 phase system

As a result of this, the three third harmonic phase voltage are in phase with each other. The effect appears in the form of circulating current at the third harmonic frequency and only felt in the zero sequence circuit. The current's magnitude is controlled by the third harmonic voltage and the third harmonic impedance of zero sequence circuit.

2.2 Triplen Harmonics and Load Conditions

In a 3-phase balanced wye system, the currents flowing to the neutral node are supposed to cancel, so that there is zero current on the neutral path. Harmonic waves may behave differently. Apart from can be modelled as current sources, harmonics also can be modelled as voltage sources [4]. Given the equation of 2nd harmonic,

$$Van2 = |E| \cos 2(wt + 0°) = |E| \cos (2wt + 0°) = |E| \cos (2wt)$$

$$Vbn\,2 = |E| \cos 2(wt - 120°) = |E| \cos (2wt - 240°) = |E| \cos (2wt + 120°)$$

$$Vcn2 = |E| \cos 2(wt + 120°) = |E| \cos (2wt + 240°) = |E| \cos (2wt - 120°)$$

Except for the negative sequence, the system will still be balanced in the presence of the 2nd harmonic. The current from the 2nd harmonic sources will still cancel in neutral wire. It can be concluded here that this is true with any even harmonic.

It is different with 3rd harmonic. 3rd harmonic voltages source equation given by:

$$Van3 = |E| \cos 3(wt + 0°) = |E| \cos(3wt + 0°) = |E| \cos(3wt)$$

$$Vbn3 = |E| \cos 3(wt - 120°) = |E| \cos(3wt - 360°) = |E| \cos(3wt)$$

$$Vcn3 = |E| \cos 3(wt + 120°) = |E| \cos(3wt + 360°) = |E| \cos(3wt)$$

From the equation, we can notice that all the waves are in phase with each other. This is well illustrated in the following figure.

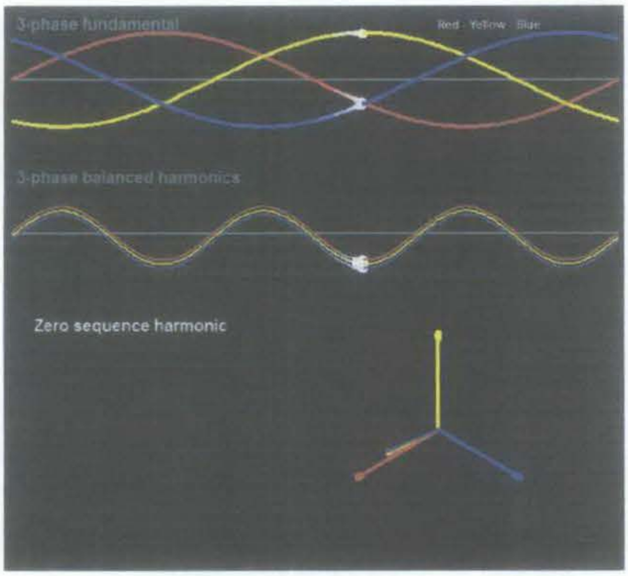

Figure 3: Third harmonic sequence

In a similar derivation as the previous equation, with current instead of voltage we can observe in neutral wire:

$$Ian3 = Ibn3 = Icn3$$

$$In = Ian3 + Ibn3 + Icn3 = I \cos(3wt)$$

If the current in the neutral wire for 2nd harmonic still cancels, the 3rd harmonic current adds, producing a very large neutral current [4].

When delta configuration is used, with the delta on the load side, there is no neutral wire for the harmonic currents to travel. The harmonics trapped and travel around the load loop.

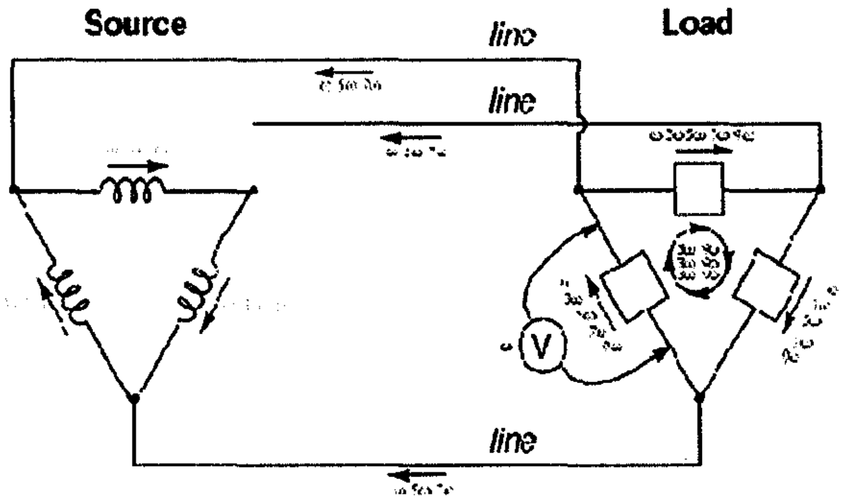

Figure 4: Triple harmonics trapped in delta loop.

As seen in the figure, the triplen harmonics currents are not travelling into the rest of the system. Therefore, the currents do not add together and cause the wave distortion as they will in a wye connected system. When going from line-to-neutral voltage to line-to-line voltage:

$$Vab = Van - Vbn \text{ and since}$$

$$Van3 = Vbn3 = Vcn3$$

We can observe that the power across the load in a delta loop due to the third harmonic is zero.

$$S = VI^*$$

$$S_L3 = (Vab3)(Iab3)^* = (Van3 - Vbn3)(Iab)^* = [E\cos(3wt) - E\cos(3wt)](Iab)^* = 0$$

The triplen harmonic currents problem will stay in the load because the delta loop traps them. This configuration is best used when the load is non-linear.

2.3 The Causes and Effects of Triplen Harmonics

The presence of triplen harmonics in the distribution system can have deleterious effects. These effects have been investigated in several researches and studies. One of the common effects is the increase of neutral earthing resistor (NER) temperature installed at generating units [5]. This effect can be observed when the generator is operating in parallel with the utility grid. In parallel operation, triplen harmonics current are noticed to be higher. During his operation, triplen harmonics continuously flow through NER which caused the emperature of NER to increase.

Transformers also can be affected by triplen harmonics currents [6]. At full load, the normal eddy current losses are about 10% of overall loss. Eddy current losses are increase with the square of the harmonic number. Practically, for a transformer that supplying for IT comprising load, the total losses would be twice as high compared to non-linear load. This results in shorter lifespan of transformer and also increases the operating temperature.

To offset the effect of low power factor, many industrial and commercial electrical systems installed capacitor banks [7]. Most capacitors are designed to operate at a maximum of 110% of rated voltage and at 135% of their kVar ratings. These limitations are frequently exceeded in a power system characterized by large voltage or current harmonics. The outcome will be the failure of capacitor banks. Unfiltered harmonic currents in the power system find their way into capacitor banks because capacitive reactance is inversely proportional to frequency. These banks attract harmonic currents, becoming overloaded.

Apart from that, one study has showed that triplen harmonic currents also increase the neutral to earth voltage [8]. Neutral to earth voltage (NEV) is the measurement of voltage between system neutral and earth surface. This measured voltage depends on the flowing of neutral current between neutral and earth, neutral impedance and earth impedance. Triplen harmonic currents is additive in the neutral. The neutral to earth voltage will increase when the neutral current is increased.

Telephone lines and communication system also experienced disturbances because of triplen harmonics. This disturbance is due to magnetic and electric fields produced by harmonics currents and voltages [9]. This disturbance is a function of both amplitude and frequency of the harmonic components. This disturbance affected the performance of the telephone lines such as the audio quality.

Triplen harmonics voltages can also cause voltage distortion [6]. The supply has source impedance and because of this, the harmonic load currents give rise to harmonic voltage distortion on the voltage waveform. Study showed that the distorted voltage drop in the cable impedance is caused by the distorted load current drawn by non-linear loads. This distorted voltage waveform is applied to all other loads connected to the same circuit, causing harmonic currents to flow in them.

2.4 Triplen Harmonics Produced By Synchronous Generator

Synchronous generator is one of the sources that generate harmonic voltages. This harmonic voltages drive triplen harmonic currents [5]. At no load, only triplen harmonics voltages are present at output terminals of generator. Triplen harmonics currents only exist when generator start to supply a load [1]

Synchronous machine represent a source of harmonics currents on two counts, which is the non-linear magnetic characteristic due to magnetic saturation and also the frequency conversion effect [10]. When a synchronous generator is supplying an unbalanced 3 phase load, it may experience flow of a negative sequence current in the rotor, which may induce triplen harmonics at the stator. This is what we call frequency conversion effect.

The cause of triplen harmonics voltages produced by synchronous generator can be different under various loads. At no load, salient pole shape and the concentrated field winding of synchronous generator becomes the main reason. These two reasons also also contribute to the triplen harmonics at balanced and unbalanced load. The difference is that at balanced load, triplen harmonics also contributed by direct-axis armature reactance. The same goes to unbalanced load with the addition of the effect of backward field magnetomotive force (mmf) [11].

Investigation conducted in [5] revealed that synchronous generator produced triplen harmonics currents that flow in reverse direction of load flow. This can be observed when the synchronous generator is in parallel connection with the utility grid. Triplen harmonics currents actually flow through zero sequence impedance of the electrical network.

Triplen harmonics also noticed to be high when synchronous generator operating in island mode is connected to utility grid. This phenomenon is caused by utility power supply that acts as short circuit to triplen harmonic currents. System capacitance of directly connected generators in island distribution system provides zero sequence paths for triplen harmonics currents to return to generator neutral which can cause overloading at generator neutral [12].

The characteristics of this harmonics produced by synchronous generator have to be done in order to reduce it. This harmonics, especially triplen harmonics, can have different characteristics under various loads which is important to be studied.

?.5 Cable Capacitance

Any two conductors separated by a distance can store a charge. So any two wires in a cable or harness can store a charge. The term "Capacitance" describes the ability of two conductors (separated by insulation) to store a charge. Capacitance is affected by the distance between the conductors and the insulation around the conductors. As the conductors get closer together or have more surface area (longer wires, shields etc.) the capacitance will increase.

If a voltage signal is being transmitted by a twisted pair or coaxial cable, the insulation on the individual wires becomes charged by the voltage within the circuit. Since it takes a certain amount of time for the cable to reach its charged level, this slows down and interferes with the signal being transmitted.

Harmonic overloading of capacitors

The current flow in a circuit is dictated by the impedance of a circuit. As the supply impedance is generally considered to be inductive, the network impedance increases with frequency while the impedance of a capacitor decreases. This encourages a greater proportion of the currents circulating at frequencies above the fundamental supply frequency to be absorbed by the capacitor, and all equipment associated with the capacitor.

In certain circumstances such currents can exceed the value of the fundamental capacitor current. These currents in turn increased voltage to be applied across the dielectric of the capacitor. The harmonic voltage due to each harmonic current added arithmetically to the fundamental voltage dictates the voltage stress to be sustained by the capacitor dielectric and for which the capacitor must be designed.

Capacitors of the correct dielectric voltage stress must always be used in conditions of harmonic distortion to avoid premature failure.

CHAPTER 3

METHODOLOGY

3.1 Methodology

The research methodology is divided into five stages. The first stage is the preliminary research work on the project. Next is to model the synchronous generator as triplen harmonics source under various loads using the PSCAD software. The third stage is the testing of the model by doing lab experiment followed by the results analysis and discussion. The last stage is the final documentation that compiles all the research works and the outcomes of the project.

3.1.1 Preliminary Research Work

At this stage, the research on triplen harmonics will be conducted by compiling information from previous journals, articles, technical papers and various books on related subject. Apart from that, the research on the effects of triplen harmonics and the sources of triplen harmonics also been conducted using the same method. Synchronous generator will be the main subject as one of the triplen harmonics source.

3.1.2 Lab Experiment

The expected results from the experiment are to see whether triplen harmonics currents are affected by the capacitor that acts as a cable capacitance.

During the experiment, synchronous generator and loads will be connected in 3 phase 4 wire system. Capacitor will be connected in parallel with the generator and load to act as a cable capacitance. The load and capacitor values will be increased and the value of triplen harmonics will be recorded. The purpose in doing this is to see whether triplen harmonics is affected by capacitor when we increase the value of capacitor.

The measurement is done at three different measuring points. The first point is at the generator, the second point is at the load and the third point is at the capacitor. The purpose of this is to see how triplen harmonics behave at each point.

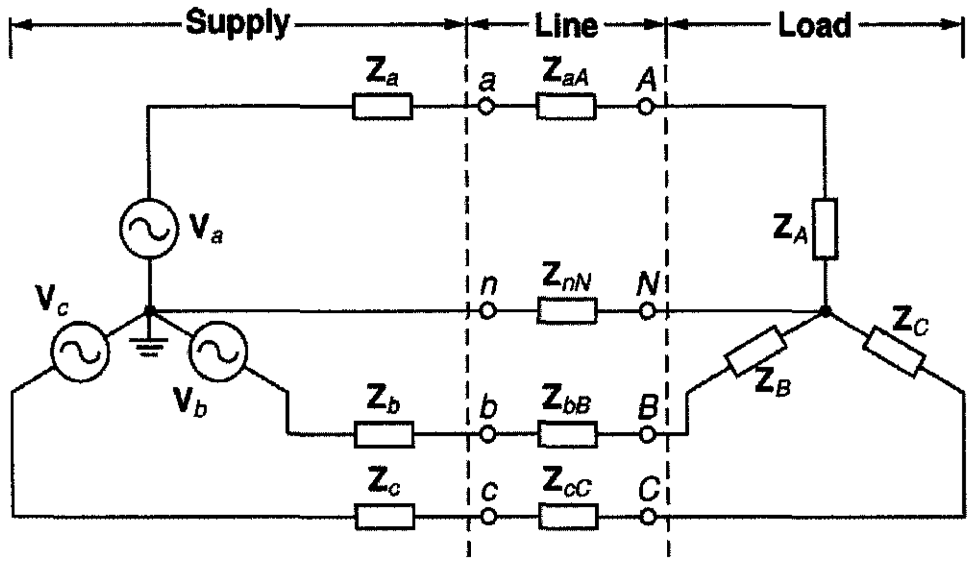

Figure 5: Four wire balance three phase circuits

3.1.3 Model Development

After the data from experiment has been collected, the project will proceed with model simulation. The purpose of this simulation is to find the right source or power supply to use during the simulation. There are many different 3 phase sources that can be used in the PSCAD. The objectives of using the experiment data is to find which sources can give the most accurate data.

The circuit setup of the model will be based on experiment setup. Below is a few example of modelling in PSCAD after the experiment data has been gathered.

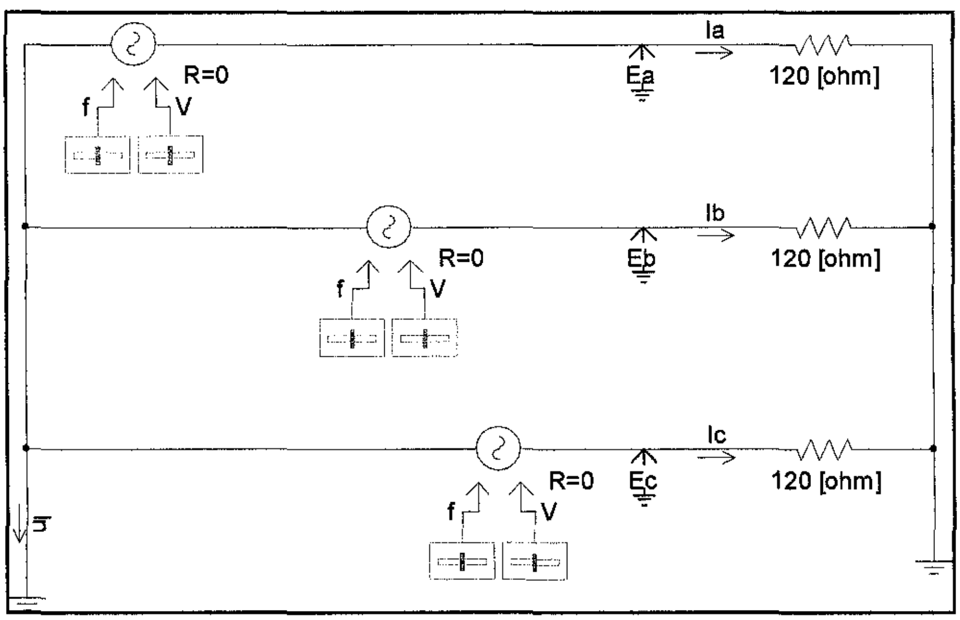

Figure 6: PSCAD model of synchronous generator connected to balanced resistive load

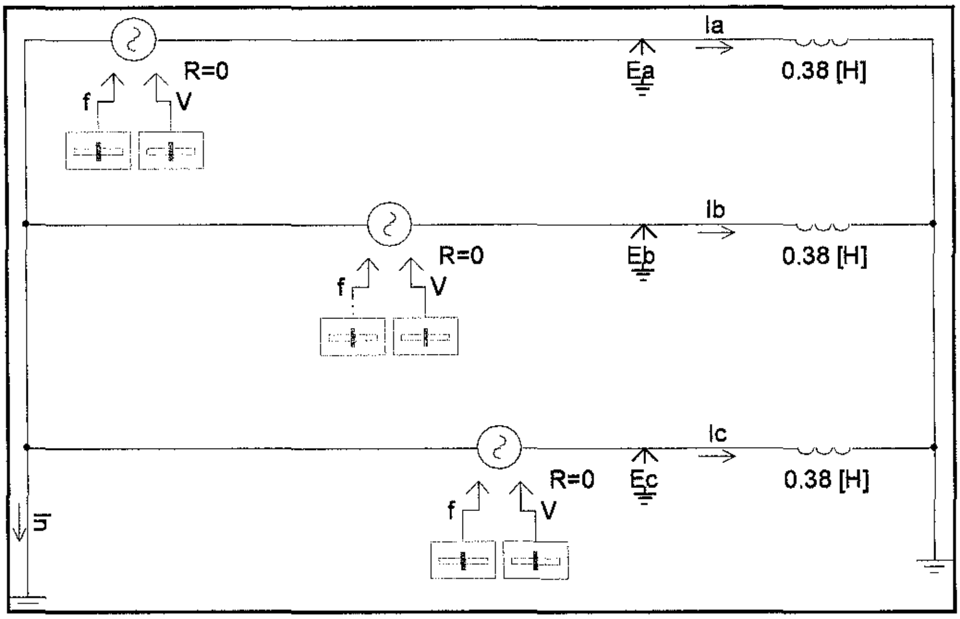

Figure 7: PSCAD model of synchronous generator connected to balanced inductive load

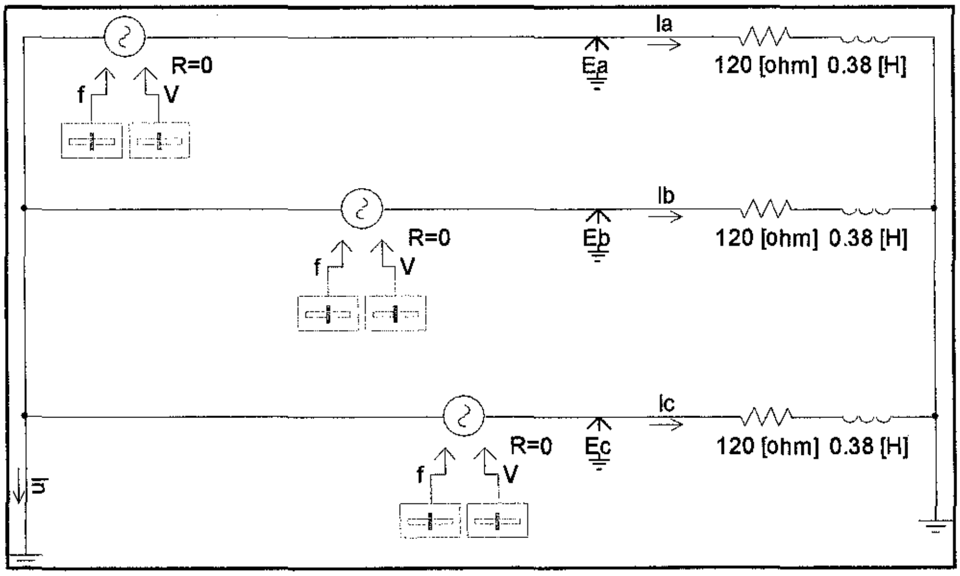

Figure 8: PSCAD model of synchronous generator connected to balanced resistive load and inductive load

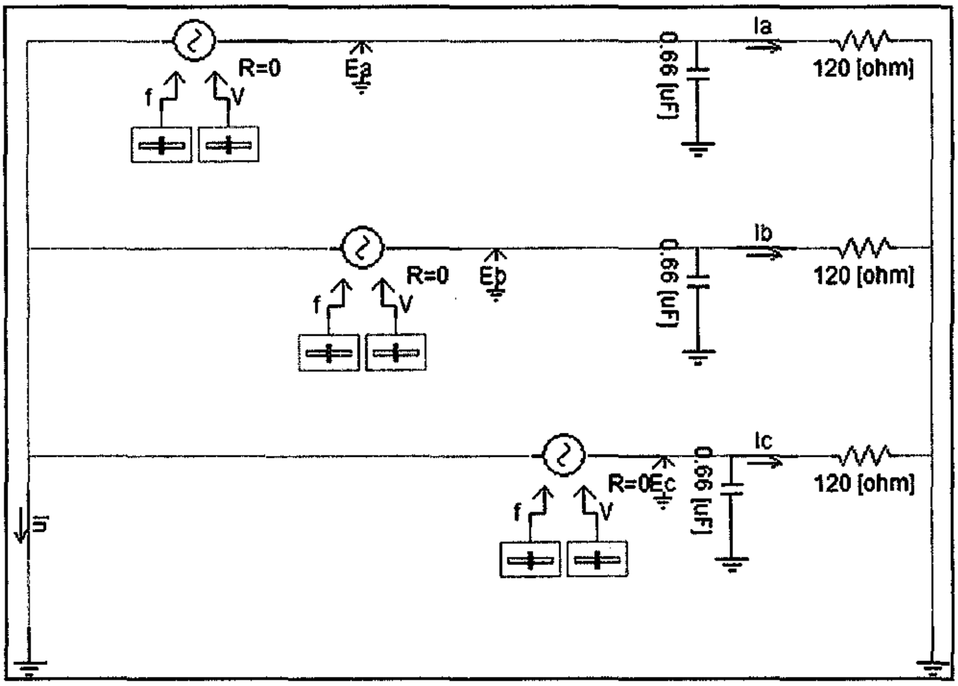

Figure 9: PSCAD model of synchronous generator connected to balanced resistive load and capacitor is introduced at each phase wire

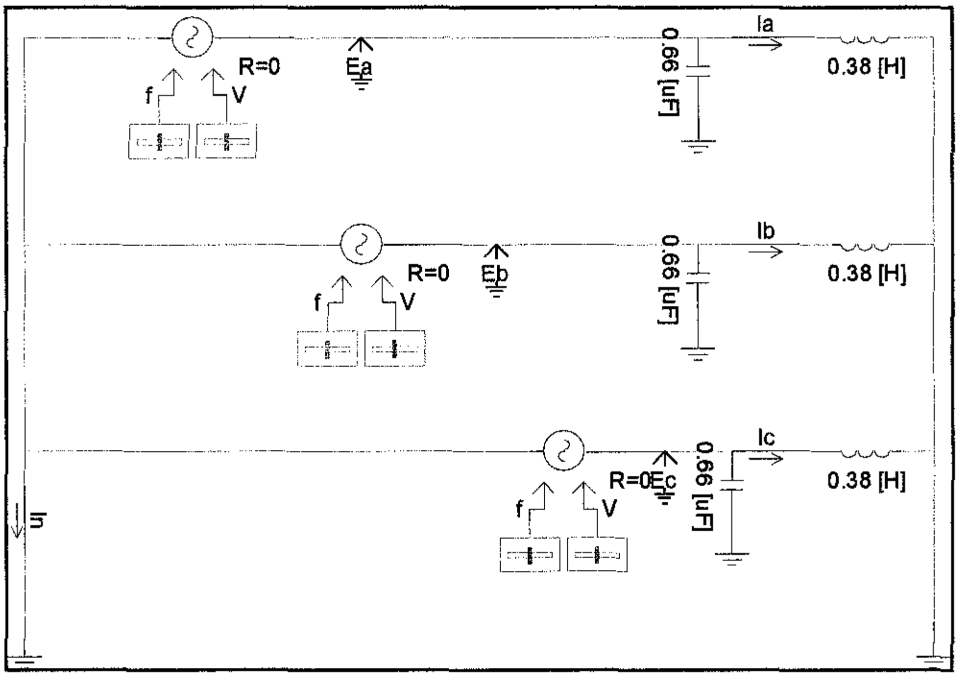

Figure 10: PSCAD model of synchronous generator connected to balanced inductive load and capacitor is introduced at each phase wire

3.1.4 Results analysis and discussion

The simulation results will be analysed and discussed with the supervisor and experts. The model will be evaluated to make sure it meets the requirements of the project. The simulation will be re-run for further investigation to improve the results if necessary.

3.1.5 Final Documentation

The research works, methods and outcomes of the project will be documented for future use. All of the documents required for the project will be done continuously starting at the early stage of the project until the last stage so as to keep track on the project.

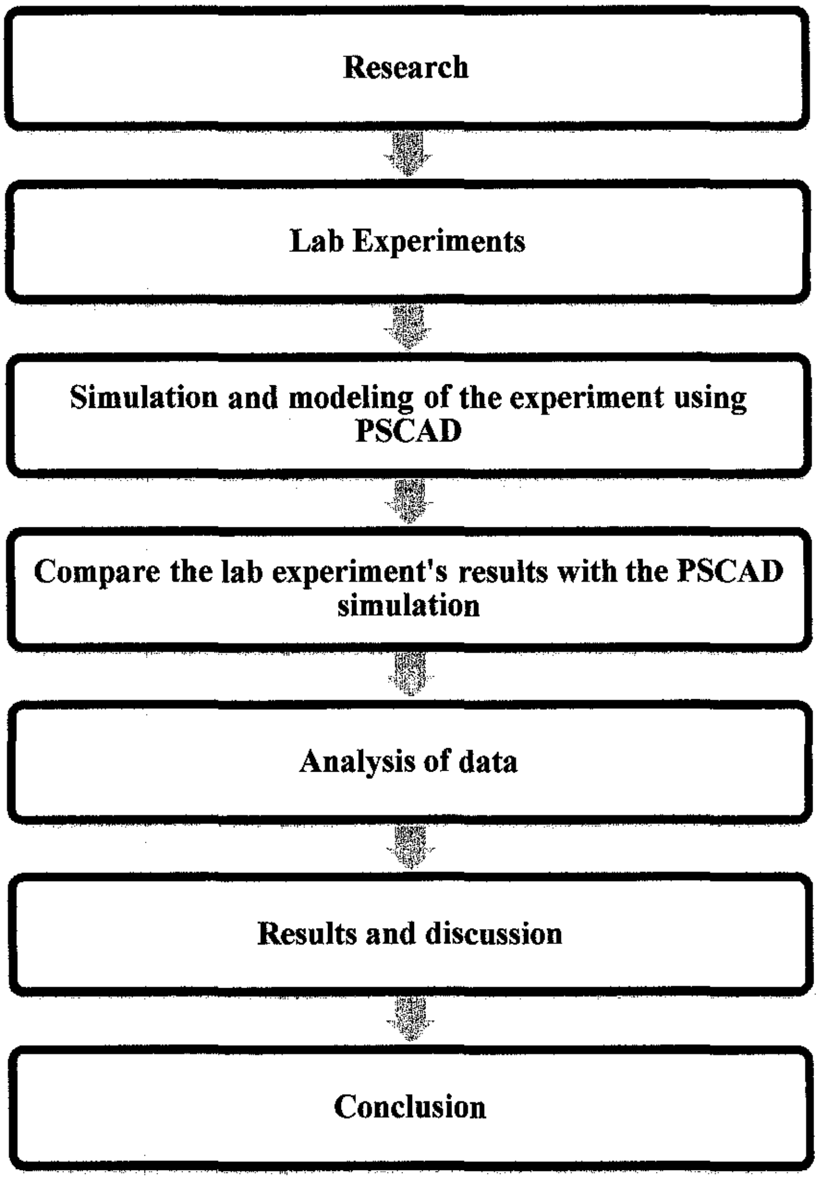

Figure 11: Flow Chart

3.2 Gantt Chart

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection and Confirmation of Project Title	■	●												
2	Preliminary Research Work on Related Topics		■	■	■	■									
3	Submission of Extended Proposal					●									
4	Model Development in PSCAD Software						■	■	■	■	■	■	■	■	■
5	Proposal Defence								■	■					
6	Lab Experiment									■	■	■	■	■	■
7	Submission of Interim Draft Report												●		
8	Submission of Interim Final Report														●

■ Process

● Milestone

CHAPTER 4

RESULTS AND DISCUSSION

l.1 Lab Experiment Results Analysis and Discussion

[he result gathered from the experiment has been documented and analysed. The objective of he analysis is to find whether increasing cable capacitance, in this case the value of :apacitor, affects how triplen harmonics behave in a power system. The analyses have been ;eparated to 3 different analyses which is:

a. Comparison of third harmonics currents when single generator connected to balanced resistive, inductive and resistive plus inductive load.
b. Comparison of third harmonics currents when single generator connected to balanced resistive load and each of the phase wire connected to capacitor that acts as cable capacitance. The load impedance and capacitor increased gradually.
c. Comparison of third harmonics when single generator connected to balanced inductive load and each of the phase wire connected to capacitor that acts as cable capacitance. The inductive load impedance and capacitor increased gradually.

The reason we increase the capacitor is because we want to observe whether triplen harmonics is affected when the cable capacitance is high. Not all the results have been used for the analysis because it appears that most of them giving the same pattern. All the results can be viewed in the appendix section.

4.1.1 Balanced Resistive Load with Balanced Inductive Load and Balanced Resistive Load plus Inductive Load

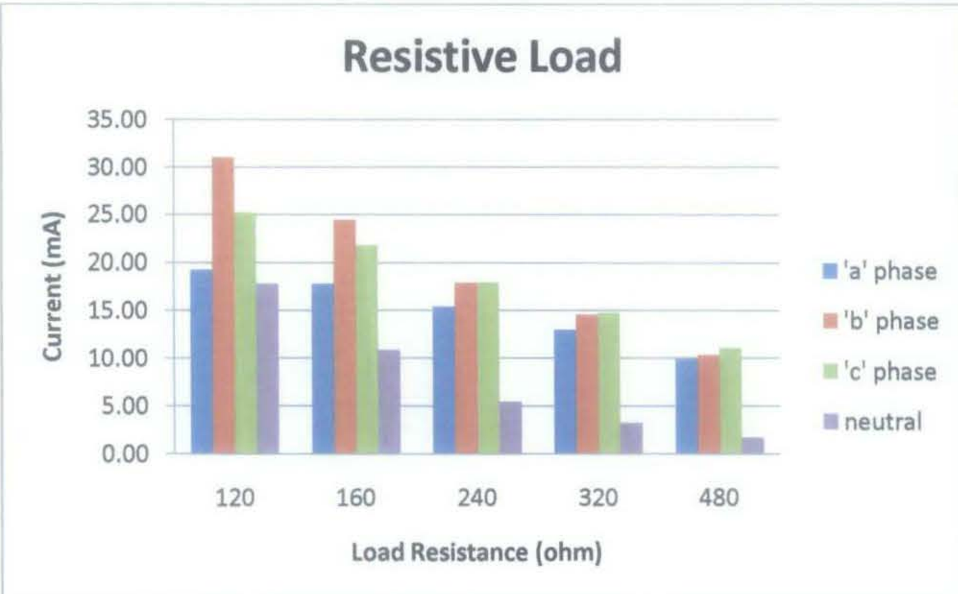

Figure 12: 3rd harmonic currents produced by synchronous generator connected to balanced resistive loads

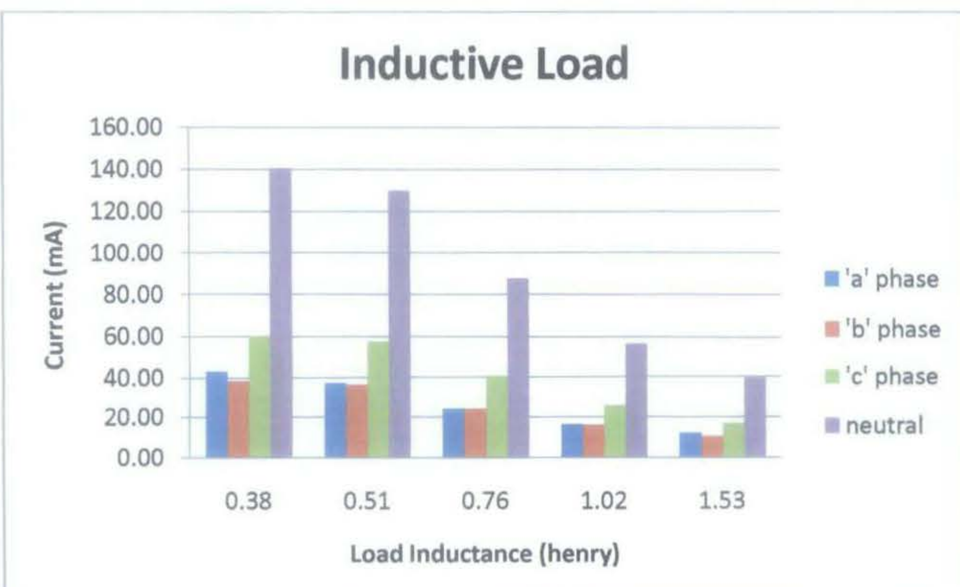

Figure 13: 3rd harmonic currents produced by synchronous generator connected to balanced inductive loads

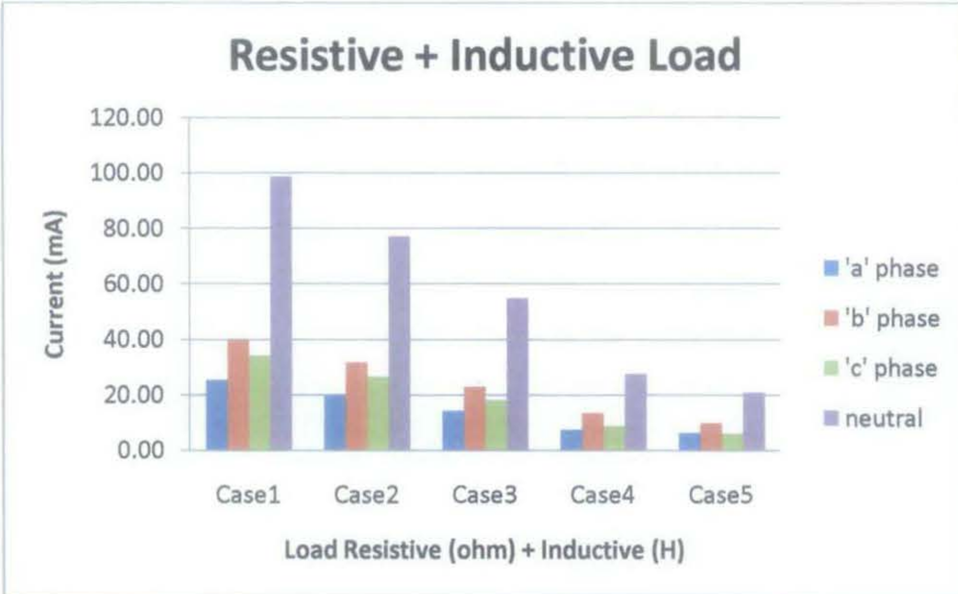

Figure 14: 3rd harmonic currents produced by synchronous generator connected to balanced resistive loads and inductive loads

In figure 12, we can observe that when the generator is connected to increasing impedance resistive load, the triplen harmonics currents is decreasing. The same thing happens when we increased the impedance of inductive load and inductive plus resistive loads. The triplen harmonics currents are decreasing.

From figure 12, 13 and 14, we can observe that third harmonic of inductive load is higher than resistive load and resistive plus inductive load. The neutral current also increased higher during the experiment with inductive load. The reason why the neutral current is very high in figure 13 is because triplen harmonics are additive in neutral. The characteristics of triplen harmonics when generator is connected to resistive load are different when inductive load are used. We can conclude here that when generator is connected to balanced inductive load, the third harmonic generated is higher.

4.1.2 Balanced resistive load without cable capacitance and balanced resistive load with cable capacitance (0.66 uF)

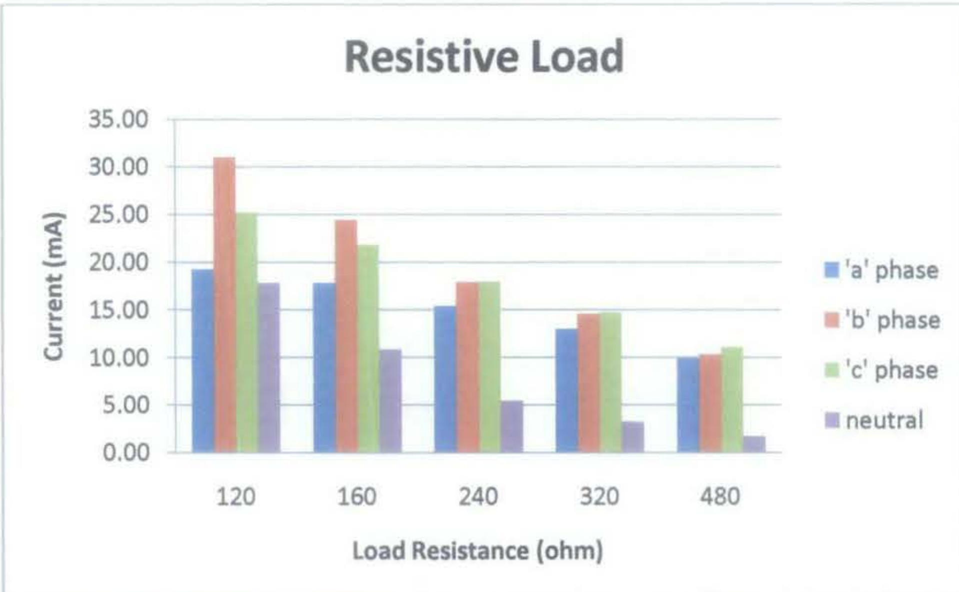

Figure 15: 3rd harmonic currents produced by synchronous generator connected to balanced resistive loads

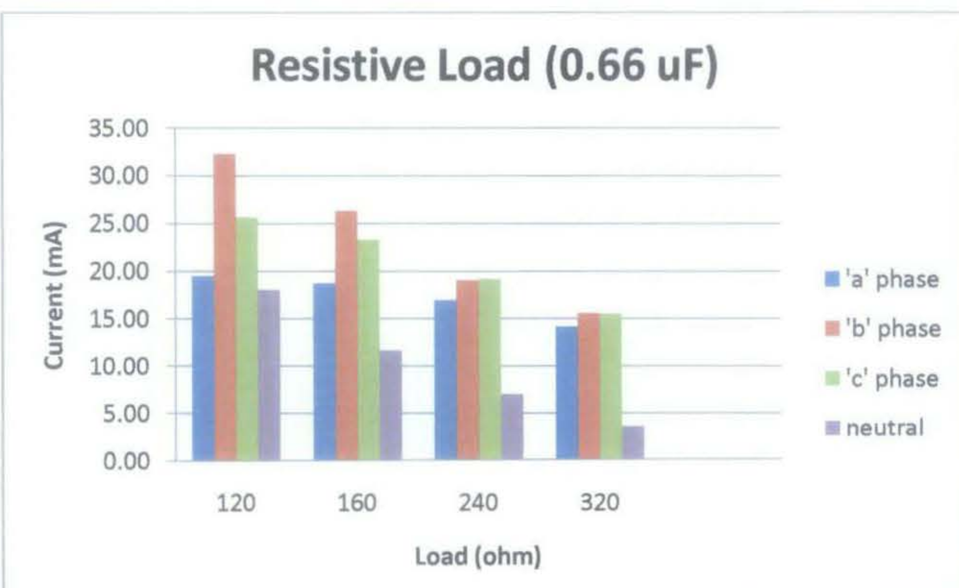

Figure 16: 3rd harmonic currents produced by synchronous generator connected to balanced resistive loads and capacitor 0.66 uF measured at generator side

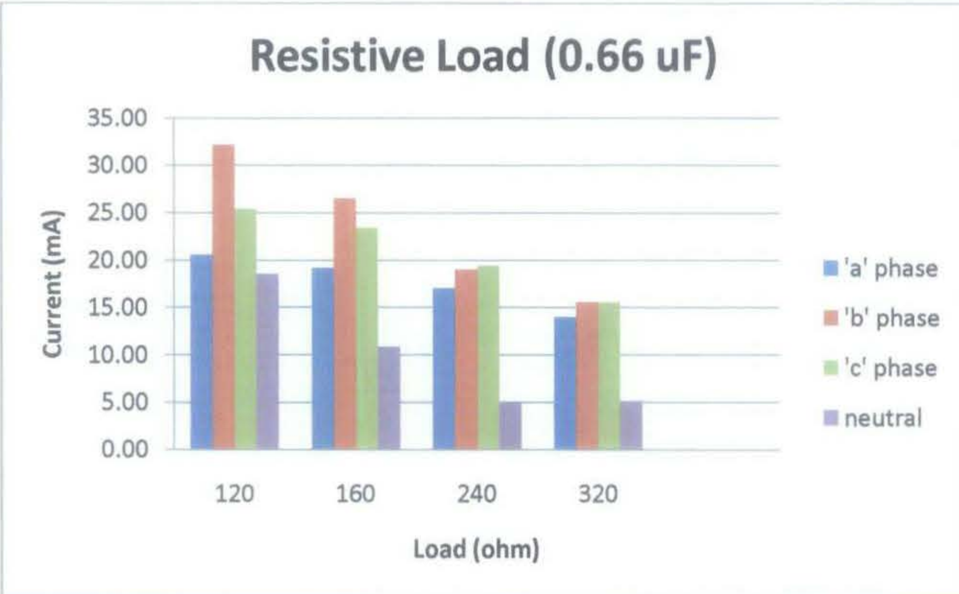

Figure 17: 3rd harmonic currents produced by synchronous generator connected to balanced resistive loads and capacitor 0.66 uF measured at load side

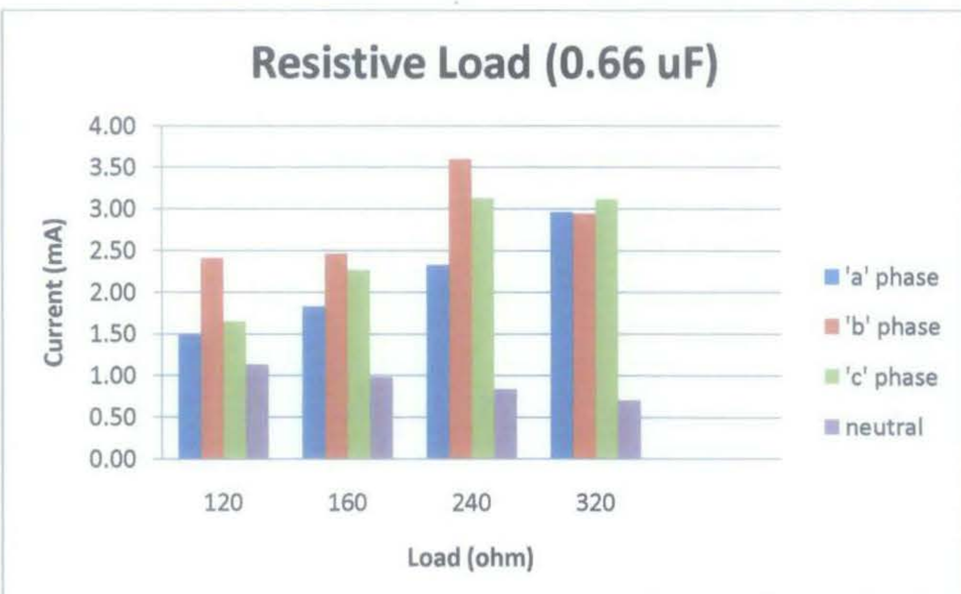

Figure 18: 3rd harmonic currents produced by synchronous generator connected to balanced resistive loads and capacitor 0.66 uF measured at capacitor side

Figure 15 is the third harmonics currents that been measured when single generator is connected to balanced resistive load only. The measurement was taken at only one point. The third harmonics currents are decreasing when the load impedance is increased.

Figure 16, 17 and 18 are the third harmonics currents measured when capacitor is introduced to each phase wire (red, blue and yellow). The measurement was made at three different ɔoints which is at the generator side (figure 16), load side (figure 17) and capacitor side figure 18).

The capacitor acts as the cable capacitance. In this part of experiment, we increased the load mpedance while the capacitor value is fixed at 0.66 uF. The purpose for this is to see how the riplen harmonics behave in a circuit with and without capacitor when single generator is connected to balanced resistive load.

From figure 15, 16 and 17, we can observe that the magnitude of triplen harmonics currents present in the power system is almost the same. The introduction of 0.66 uF capacitor didn't affect much on the magnitude of triplen harmonics currents present.

The interesting part is in figure 18. The data was measured at the capacitor point. From the graph, we can view that there is triplen harmonics current that flow into capacitor. Eventhough the magnitude is very small, but it still can be consider as triplen harmonics currents because the measuring equipment has the algorithm to calculate triplen harmonics build inside it. What we can see from the graph is that when the load impedance is increased, the triplen harmonics that being absorbed by capacitor is also increasing.

4.1.3 Generator connected to balanced resistive load with increasing cable capacitance and load

4.1.3.1 Increasing Load, Capacitor Fixed at 0.66 uF

During the experiment, the impedance of balanced resistive load is increased gradually from 120 Ohm to 320 Ohm. The capacitor value that connected to each of phase wire is fixed at 0.66 uF. The data gathered has been documented and the analysis has been done. The triplen harmonics currents are measured at 3 different points which is at the generator, load and capacitor side.

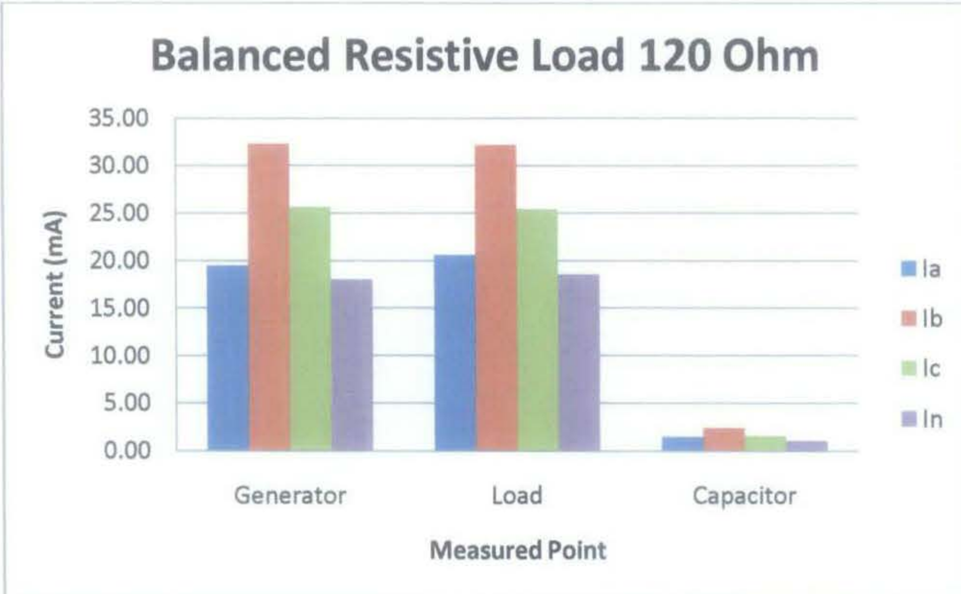

Figure 19: 3rd harmonic currents measured at various points with balanced resistive load 120 ohm

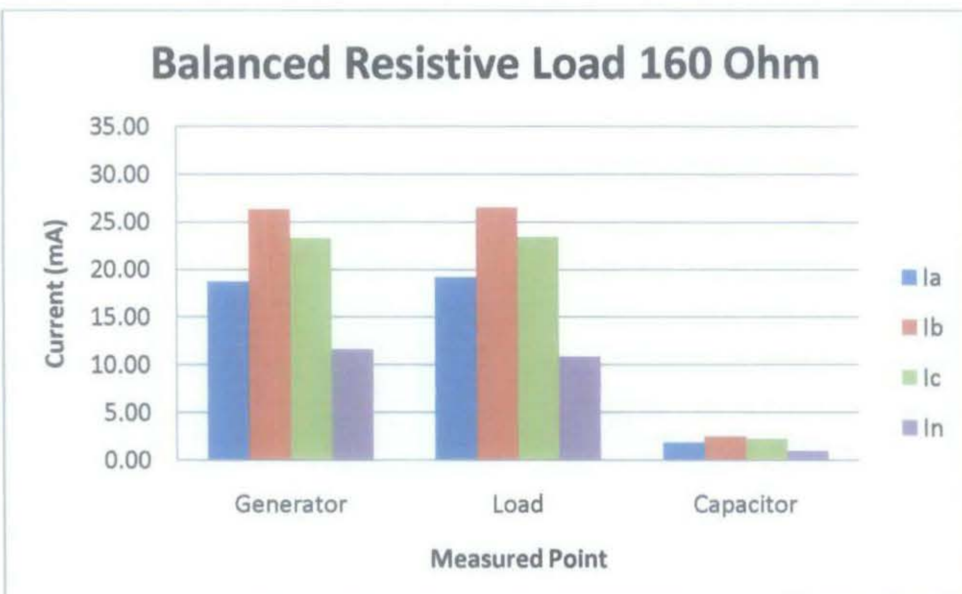

Figure 20: 3rd harmonic currents measured at various points with balanced resistive load 160 ohm

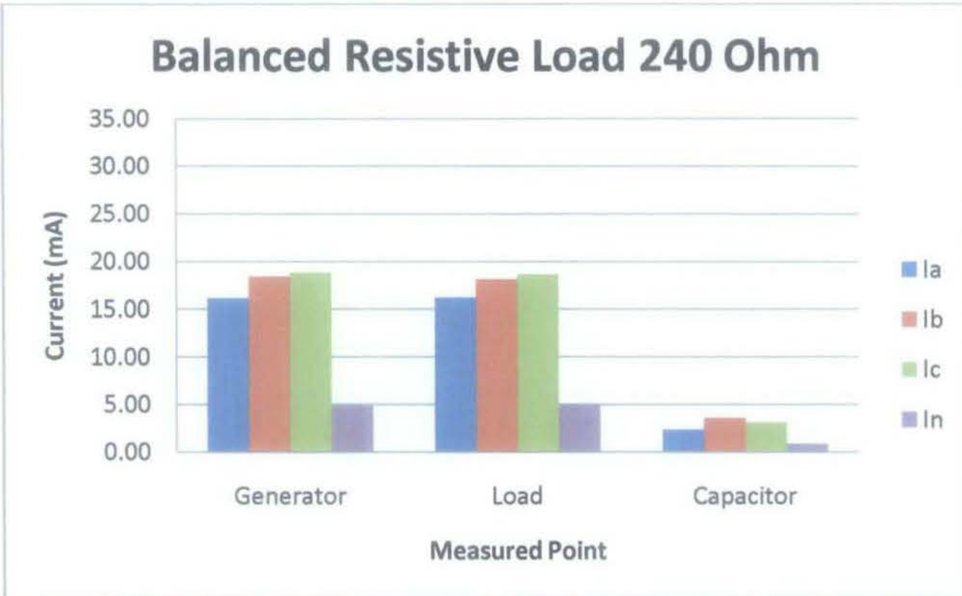

Figure 21: 3rd harmonic currents measured at various points with balanced resistive load 240 ohm

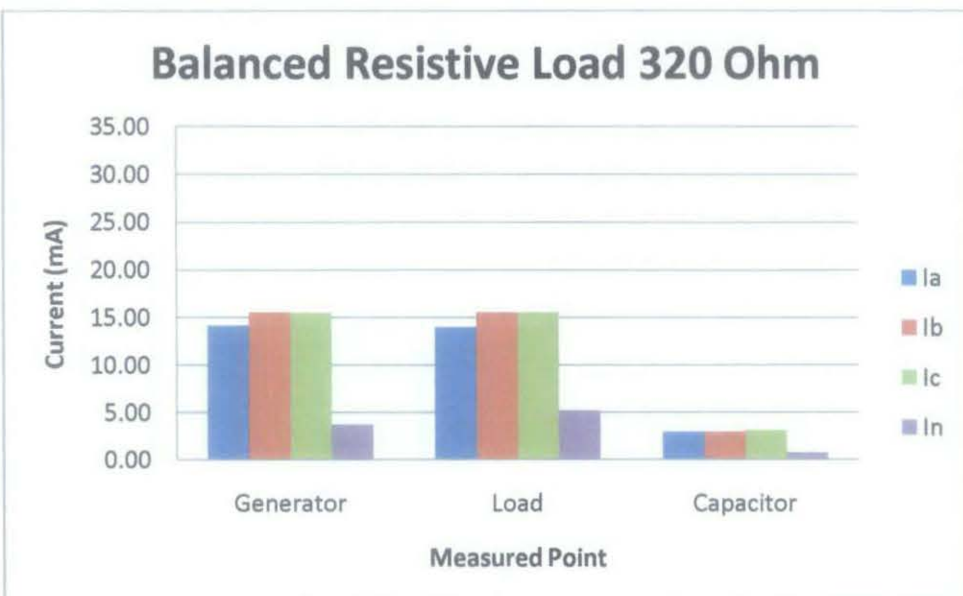

Figure 22: 3rd harmonic currents measured at various points with balanced resistive load 320 ohm

From figure 19, 20, 21 and 22, we can observe the triplen harmonics currents measured at generator and load point is decreasing. The magnitude of triplen harmonics currents that flow into capacitor otherwise did not change. If we compare between figure 19 and 22, we can see the decreasing of the triplen harmonics currents magnitude when the load impedance increase from 120 Ohm to 320 Ohm.

4.1.3.2 Increasing Load, Capacitor Fixed at 2.65 uF

During the experiment, the impedance of balanced resistive load is increased gradually from 120 Ohm to 320 Ohm. The capacitor value that connected to each of phase wire is fixed at 2.65 uF. The data gathered has been documented and the analysis has been done.

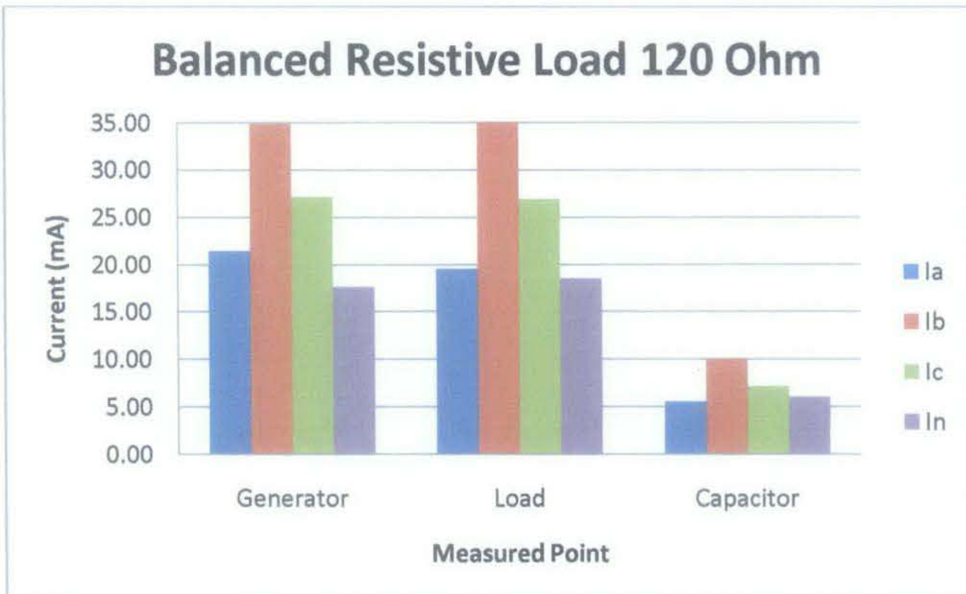

Figure 23: 3rd harmonic currents measured at various points with balanced resistive load 120 ohm

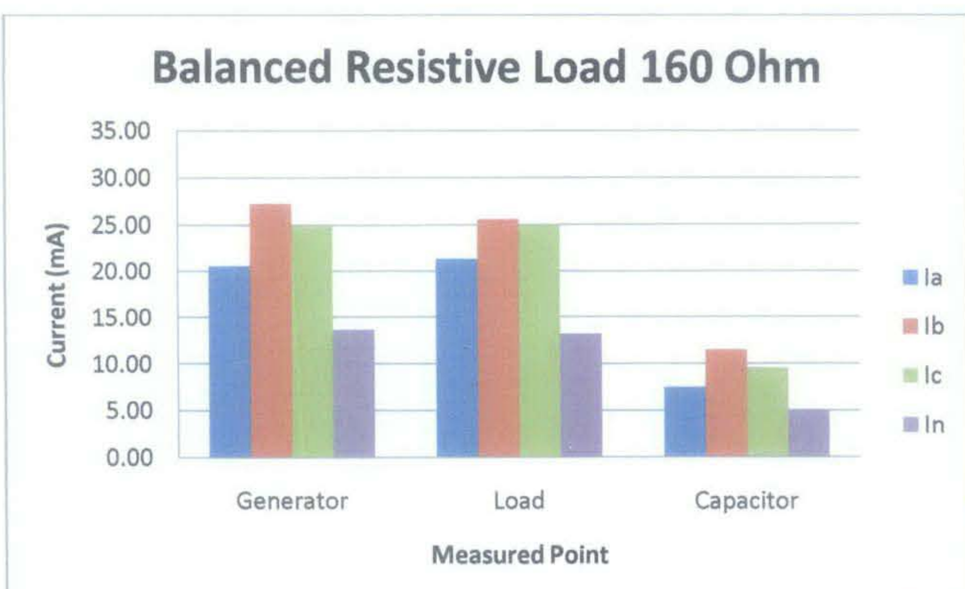

Figure 24: 3rd harmonic currents measured at various points with balanced resistive load 160 ohm

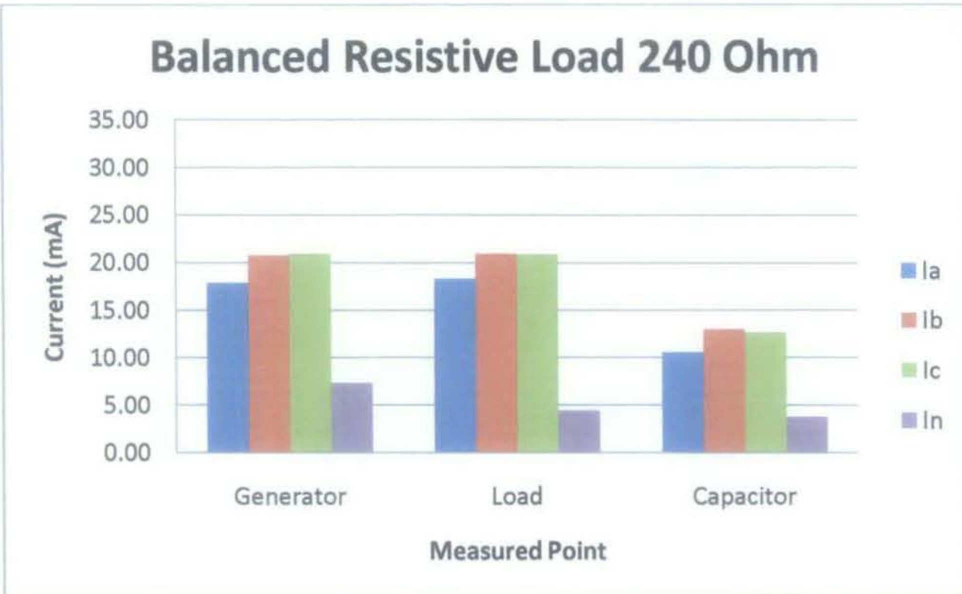

Figure 25: 3rd harmonic currents measured at various points with balanced resistive load 240 ohm

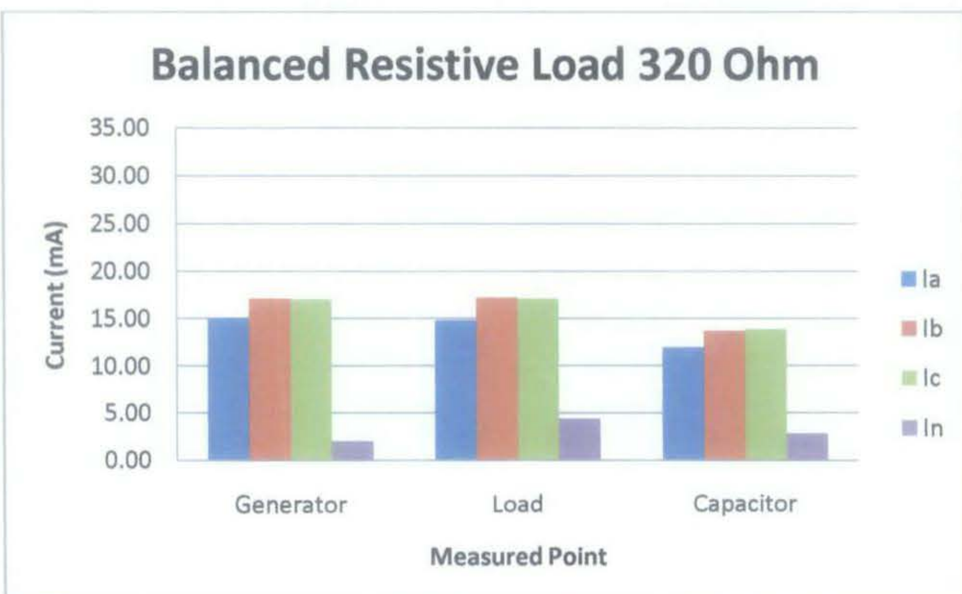

Figure 26: 3rd harmonic currents measured at various points with balanced resistive load 320 ohm

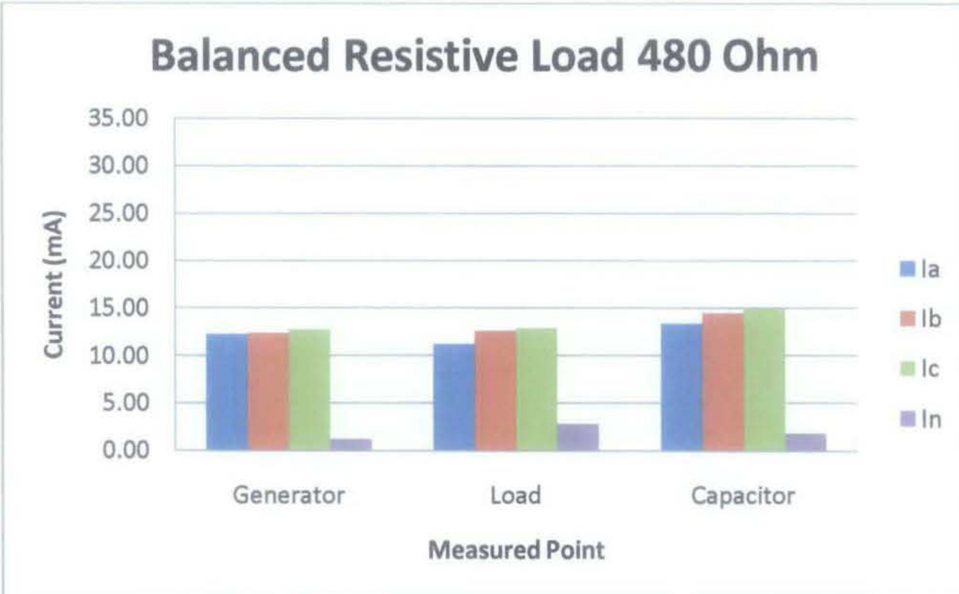

Figure 27: 3rd harmonic currents measured at various points with balanced resistive load 320 ohm

From figure 23, 24, 25, 26 and 27, we can observe that the third harmonic currents at the generator side and load side are decreasing when the impedance load is increased. There are also third harmonic currents that flow into capacitor, although the value is very small. The third harmonic currents from the capacitor side also have almost no change when we increased the impedance load. The third harmonic currents that flow into capacitor has slightly increased compared to the results from previous experiment using capacitor 0.66 uF. As we can see from figure 23, the magnitude of triplen harmonics currents at capacitor side is approximately at 10 mA while from figure 27, the magnitude of triplen harmonics currents at capacitor increased to approximately 15 mA.

The pattern is almost the same. The third harmonic currents at generator and load side are decreasing when we increased the load impedance. The current that flow into capacitor almost have no change when the load is increased, but the value become higher when the value of capacitor in increased.

From this, we can conclude that third harmonic currents flow into capacitor even at small value. The value of current flowing will increase when the capacitor's value increasing.

.1.3.3 Increasing Capacitor, Load Fixed at 120 Ohm

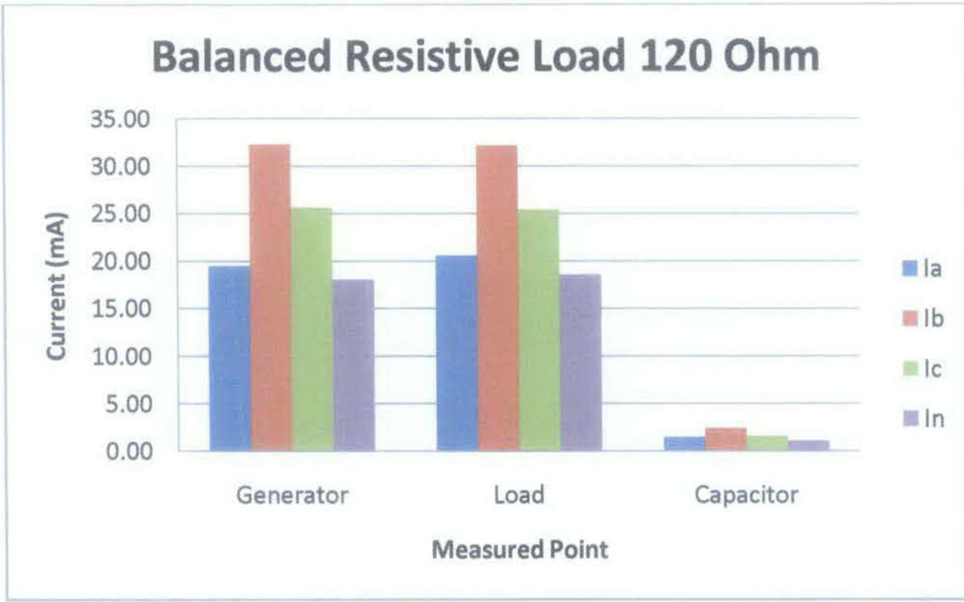

Figure 28: 3rd harmonic currents measured at various points with balanced resistive load 120 ohm and capacitor 0.66 uF

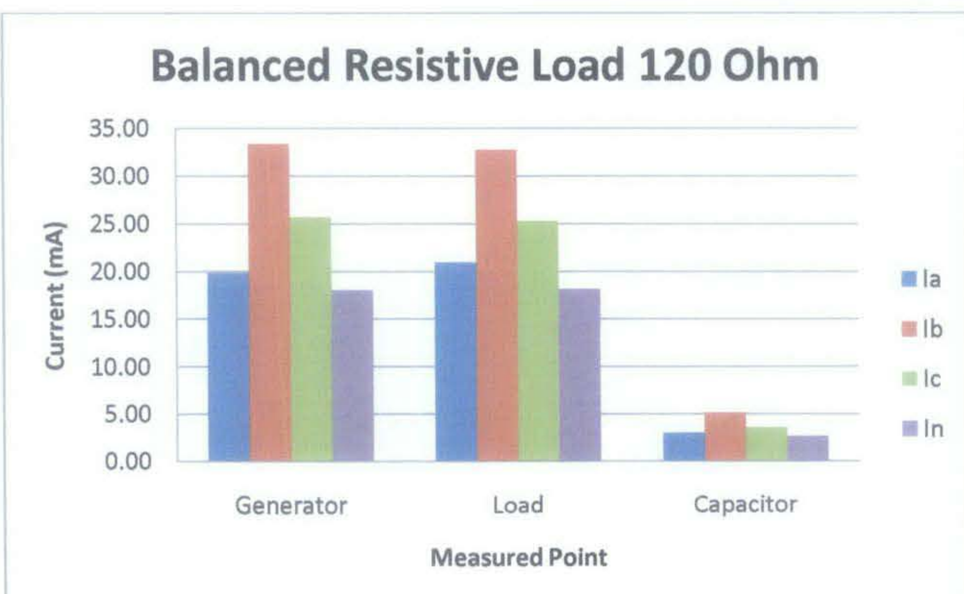

Figure 29: 3rd harmonic currents measured at various points with balanced resistive load 120 ohm and capacitor 1.33 uF

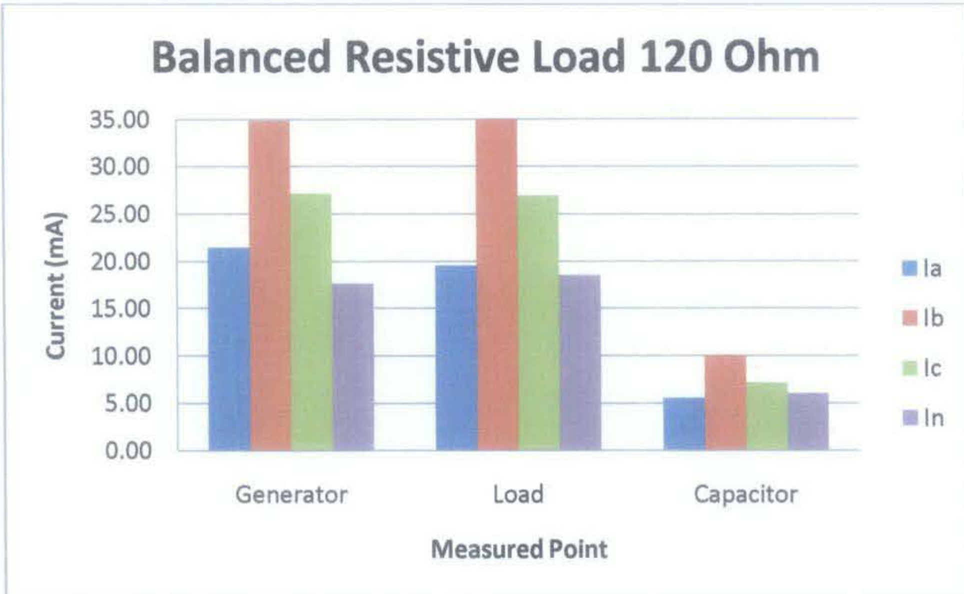

Figure 30: 3rd harmonic currents measured at various points with balanced resistive load 120 ohm and capacitor 2.65 uF

From all the results that been gathered during the experiment when single generator is connected to balanced resistive load and capacitor, we take three results when the load impedance is fixed. The purpose is to see how capacitor affects the triplen harmonics behaviour in a power system when we increased the capacitor value.

From figure 28, 29 and 30, we can observe that the magnitude of triplen harmonics at capacitor side is increasing when we increase the capacitor value. From this we can learn that the magnitude of triplen harmonics currents that flow into capacitor is increasing when the capacitor value gets higher.

4.1.4 Generator connected to balanced inductive load with increasing cable capacitance and load

4.1.4.1 Increasing Load, Capacitor Fixed at 0.66 uF

During the experiment, the impedance of balanced inductive load is increased gradually from 0.38 H to 1.53 H. The capacitor value that connected to each of phase wire is fixed at 0.66 uF. The data gathered has been documented and the analysis has been done. The triplen harmonics currents were measured at three different points which is at generator, load and capacitor side.

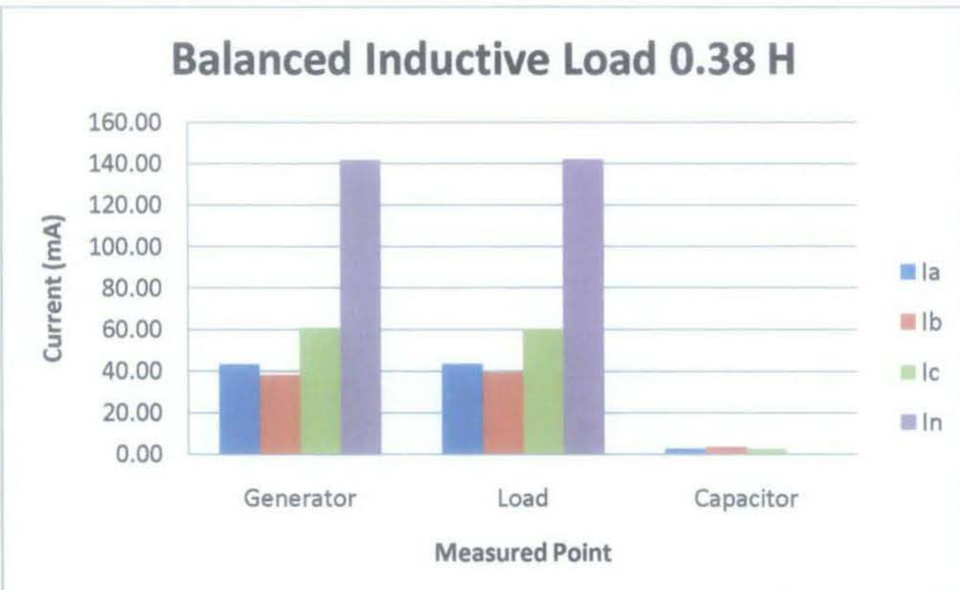

Figure 31: 3rd harmonic currents measured at various points with balanced inductive load 0.38 Henry

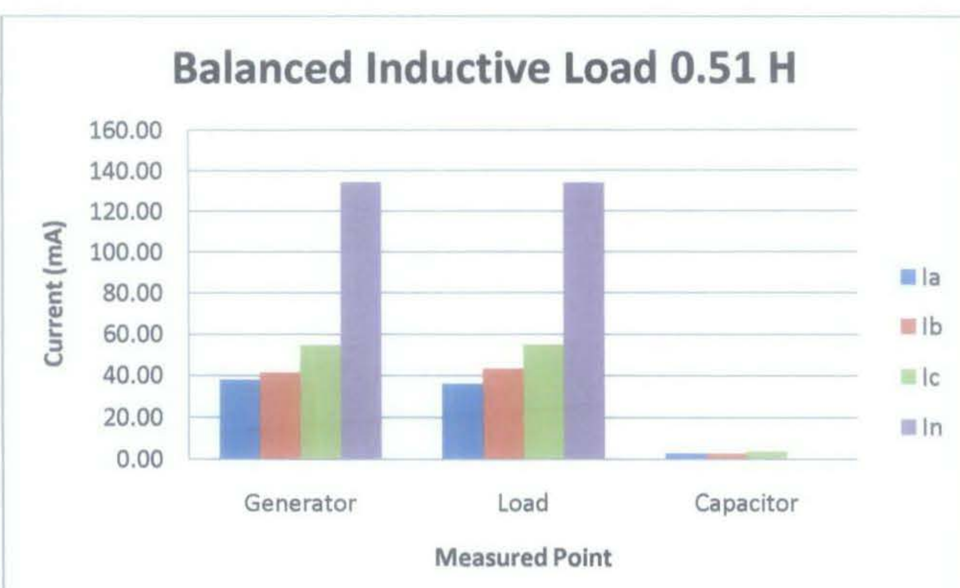

Figure 32: 3rd harmonic currents measured at various points with balanced inductive load 0.51 Henry

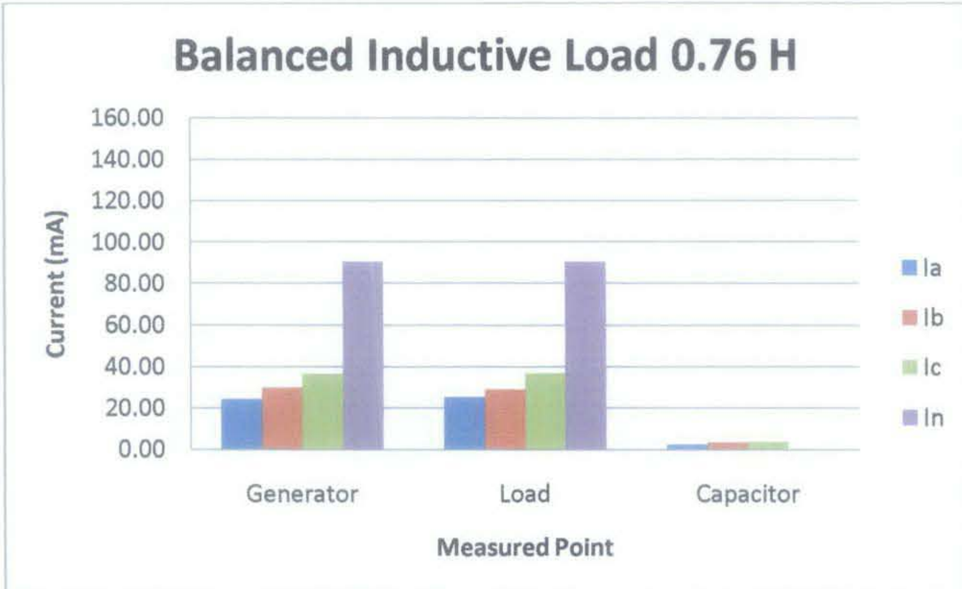

Figure 33: 3rd harmonic currents measured at various points with balanced inductive load 0.76 Henry

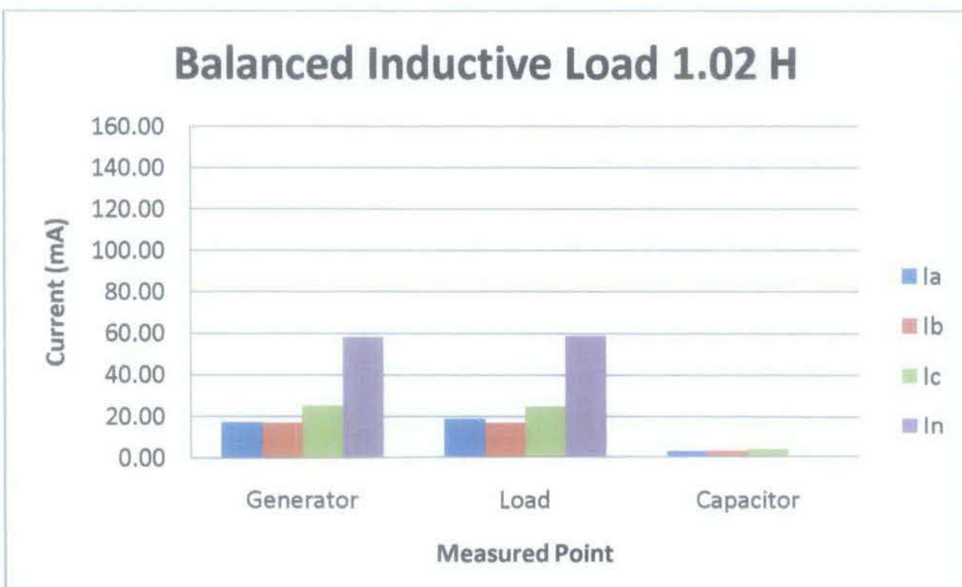

Figure 34: 3rd harmonic currents measured at various points with balanced inductive load 1.02 Henry

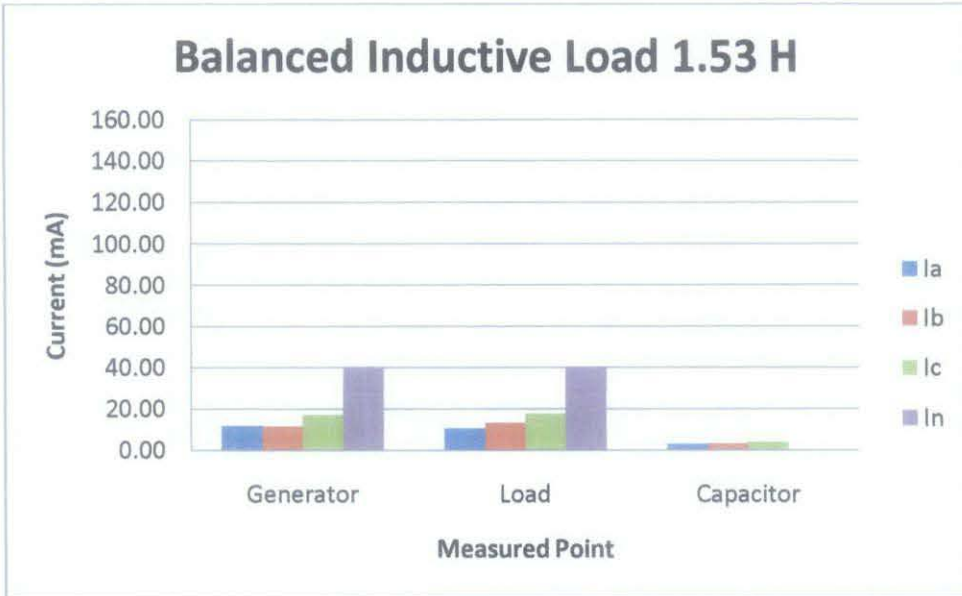

Figure 35: 3rd harmonic currents measured at various points with balanced inductive load 1.53 Henry

From figure 31, 32, 33, 34 and 35, we can notice that the third harmonic currents at the generator side and load side are decreasing when the load impedance is increased. The magnitude of third harmonic that flow into capacitor is very small. The magnitudes of third harmonic currents from the capacitor side also have almost no change when we increased the load. The value of third harmonic currents at generator and load side are also higher compared to the value when resistive load is connected.

We also can observe that the magnitude of the neutral currents is very high. This is due to the triplen harmonics nature which is additive in the neutral.

4.1.4.2 Increasing Load, Capacitor Fixed at 2.65 uF

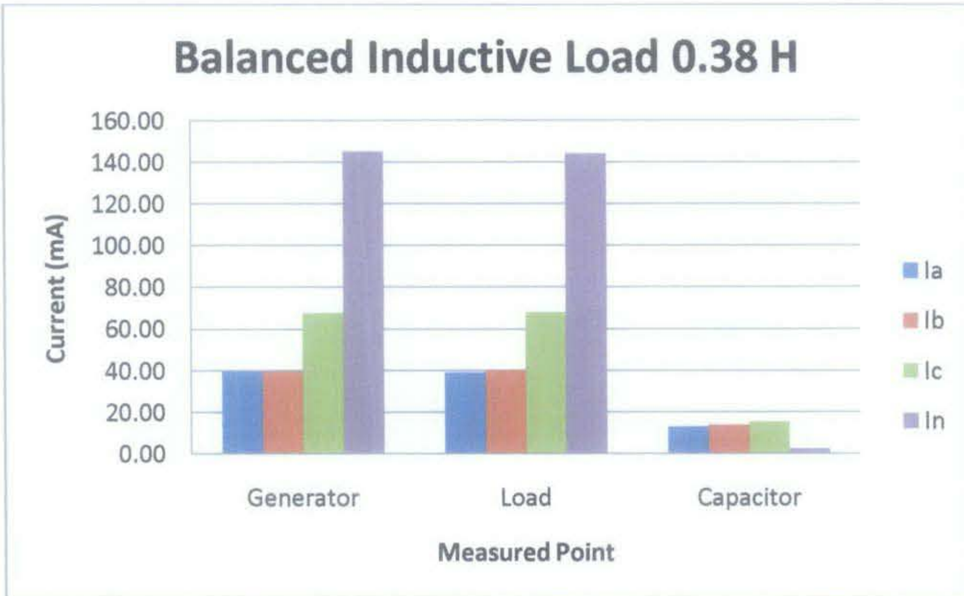

Figure 36: 3rd harmonic currents measured at various points with balanced inductive load 0.38 Henry

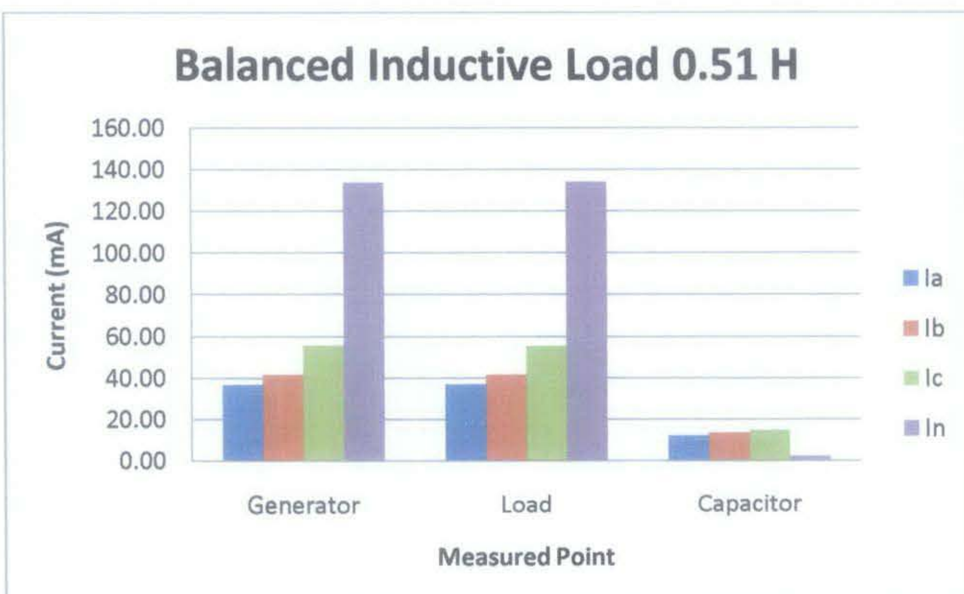

Figure 37: 3rd harmonic currents measured at various points with balanced inductive load 0.51 Henry

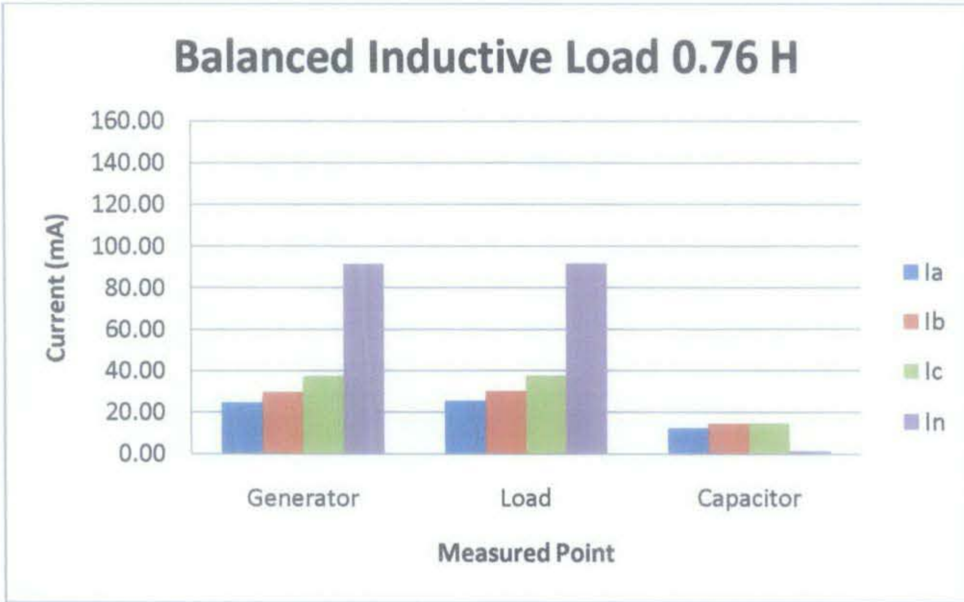

Figure 38: 3rd harmonic currents measured at various points with balanced inductive load 0.76 Henry

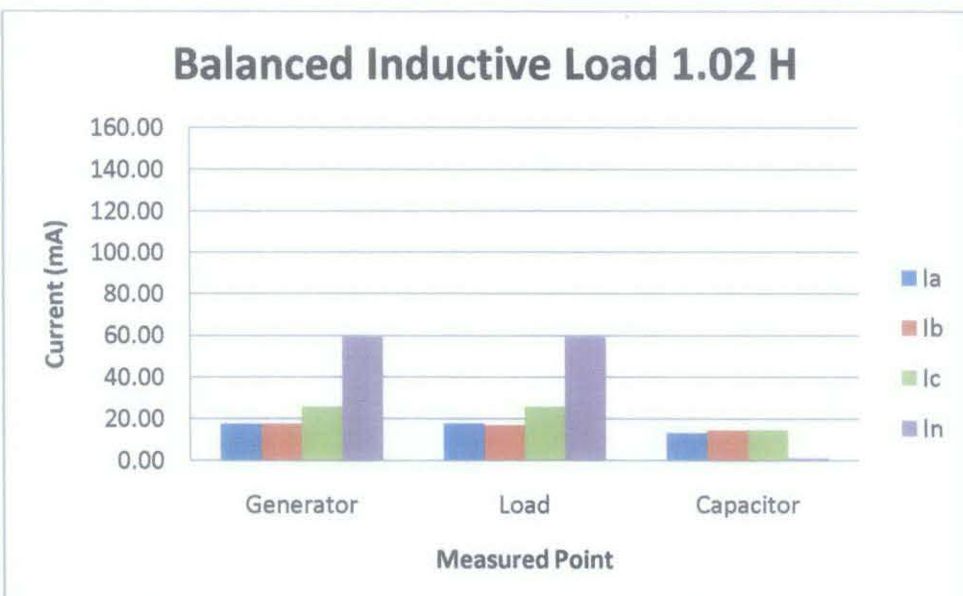

Figure 39: 3rd harmonic currents measured at various points with balanced inductive load 1.02 Henry

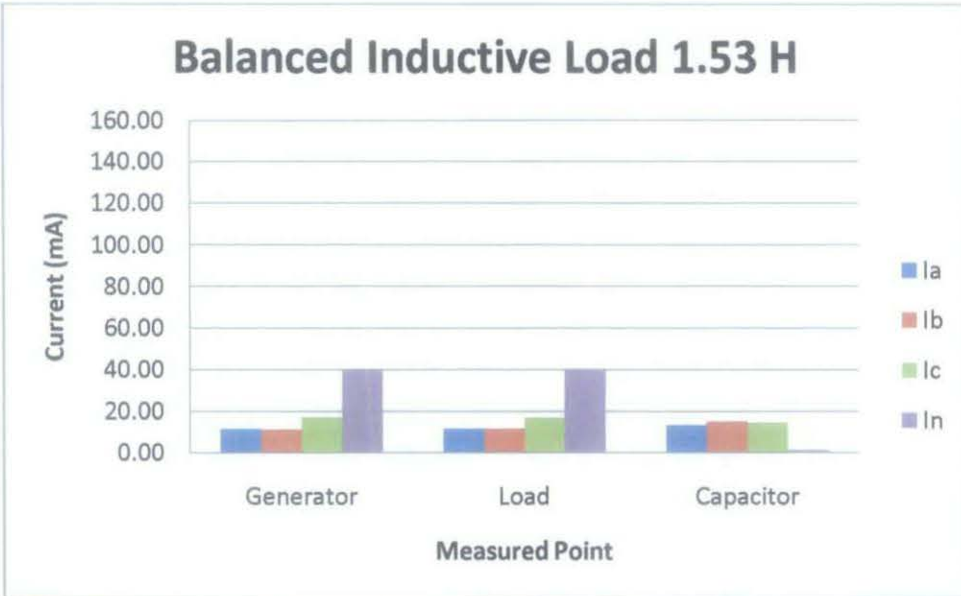

Figure 40: 3rd harmonic currents measured at various points with balanced inductive load 1.53 Henry

A few observations can be made using the above results. First, from figure 36, 37, 38, 39 and 40 we can notice that the magnitude of third harmonic currents at the generator side and load side are decreasing when the load impedance is increased. The value of third harmonic currents that flow into capacitor is very small. When we connect 2.65 uF capacitor, the third harmonics currents are visible compare when we connected 0.66 uF capacitor. The third harmonic currents from the capacitor side also have almost no change when we increased the load. The value of third harmonic currents at generator and load side almost has no changes compared to the previous experiment using 0.66 uF capacitor. Again, the value of current that flow into capacitor has increased slightly.

From the data gathered, we can conclude that when inductive load is connected to the generator, the third harmonics currents characteristic is slightly different from the third harmonics currents generated when generator is connected to resistive load. The currents at generator and load side are very high compared to resistive load. The third harmonic currents that flow into capacitor is small but increasing when the capacitor value is increased.

‌.1.4.3 Increasing Capacitor, Load Fixed at 0.38 Henry

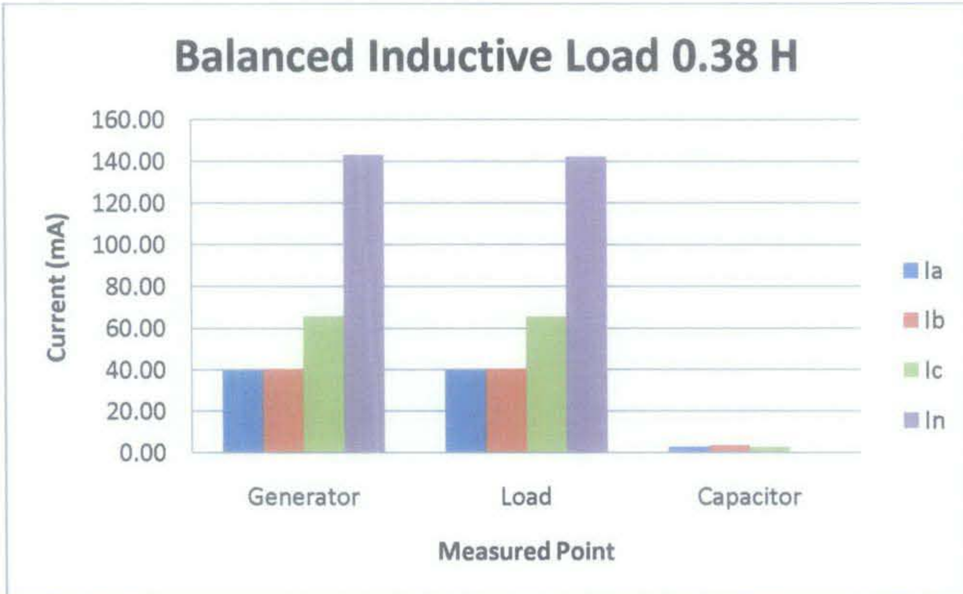

Figure 41: 3rd harmonic currents measured at various points with balanced inductive load 0.38 Henry and capacitor 0.66 uF

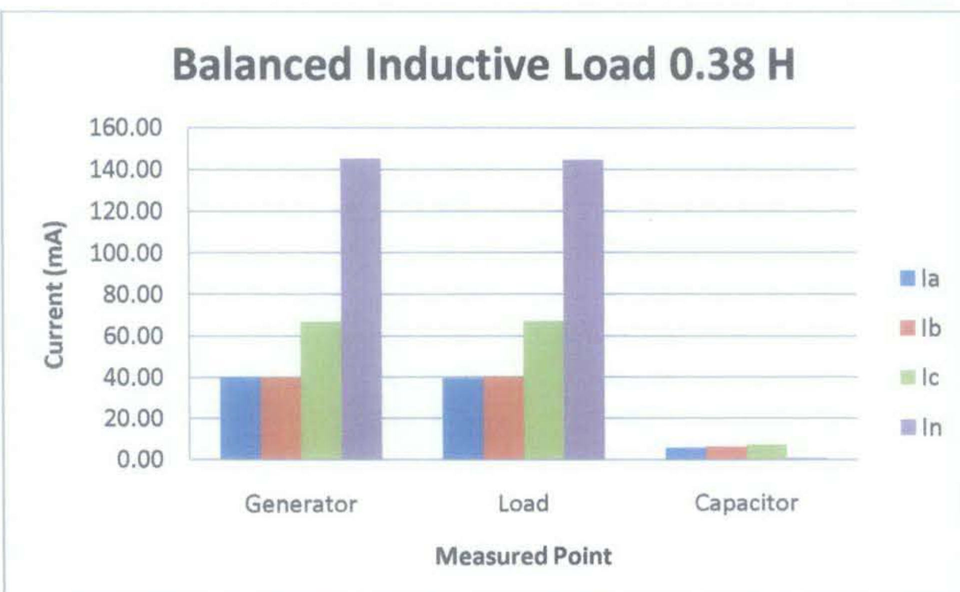

Figure 42: 3rd harmonic currents measured at various points with balanced inductive load and capacitor 1.33 uF

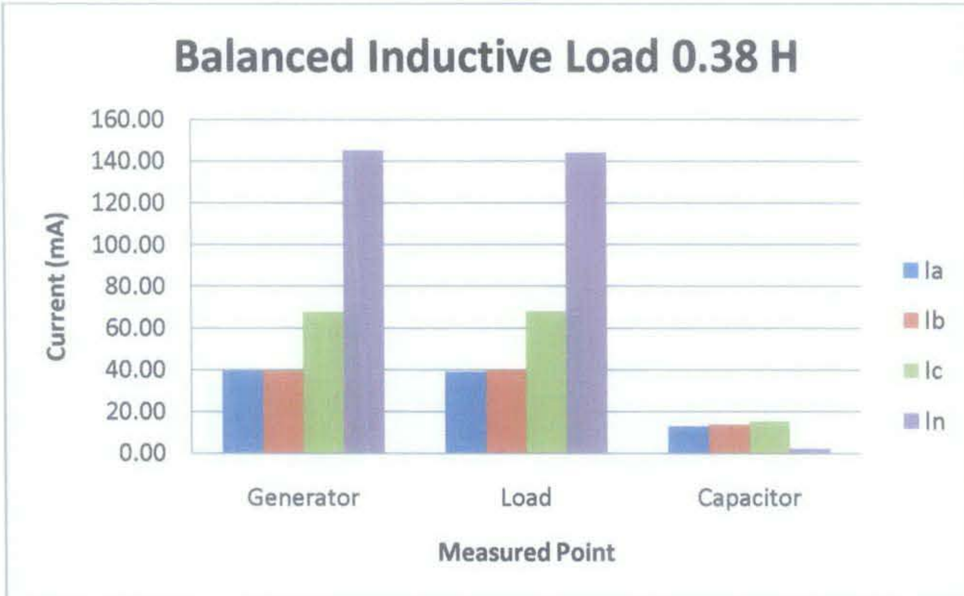

Figure 43: 3rd harmonic currents measured at various points with balanced inductive load 0.38 Henry and capacitor 2.65 uF

From figure 41, 42 and 43 it can be observed that the magnitude of third harmonic currents that flow into capacitor in increasing when the value of capacitor increased. Although the value is very small, we still can see the increment using the data. The pattern is almost the same as the third harmonics present when synchronous generator is connected to balanced resistive load. From this, we can conclude that when there is capacitor present, the third harmonic currents tend to flow into the capacitor.

4.2 Simulation Result

4.2.1 Generator with Resistive Load

In single generator connected to resistive load simulation modeling, the setup and parameter used in PSCAD software will be the same as the one used in the lab scaled experiment with five different values of resistive load which consist of 120 Ω, 160 Ω, 240 Ω, 320 Ω and 480 Ω. The triplen harmonics voltage and current will only be measured at the load side. In this simulation, the voltage source is modeled using third harmonics voltage sources. The magnitude of harmonics voltages, phase angle and frequency is injected to voltage sources.

Table 1: Triplen Harmonics Voltage And Current When Single Generator Connected To Various Resistive Load

Ohm	Va V	Vb V	Vc V	Ia mA	Ib mA	Ic mA	In mA
120	0.01061	0.01137	0.03136	0.08849	0.09478	0.2613	0.2644
160	0.001521	0.001579	0.001142	0.009507	0.009867	0.007137	0.02595
240	0.01167	0.01225	0.01597	0.04864	0.05103	0.06653	0.1661
320	0.0592	0.06446	0.06334	0.185	0.2014	0.1979	0.5843
480	0.003715	0.00506	0.008986	0.007741	0.01054	0.01872	0.03697

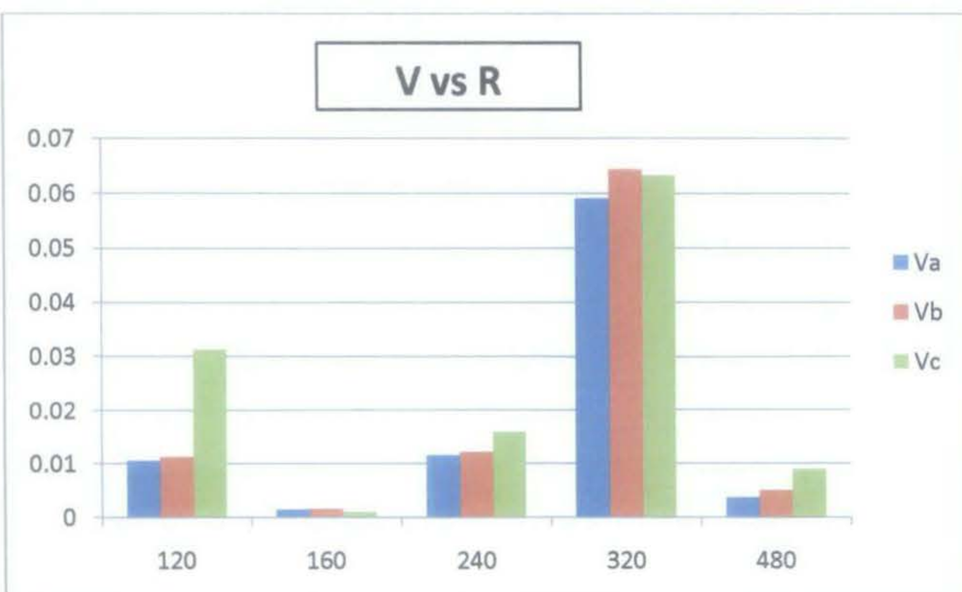

Figure 44: Graph Of Triplen Harmonics Voltage Vs Resistance When Single Generator Connected To Various Resistive Load

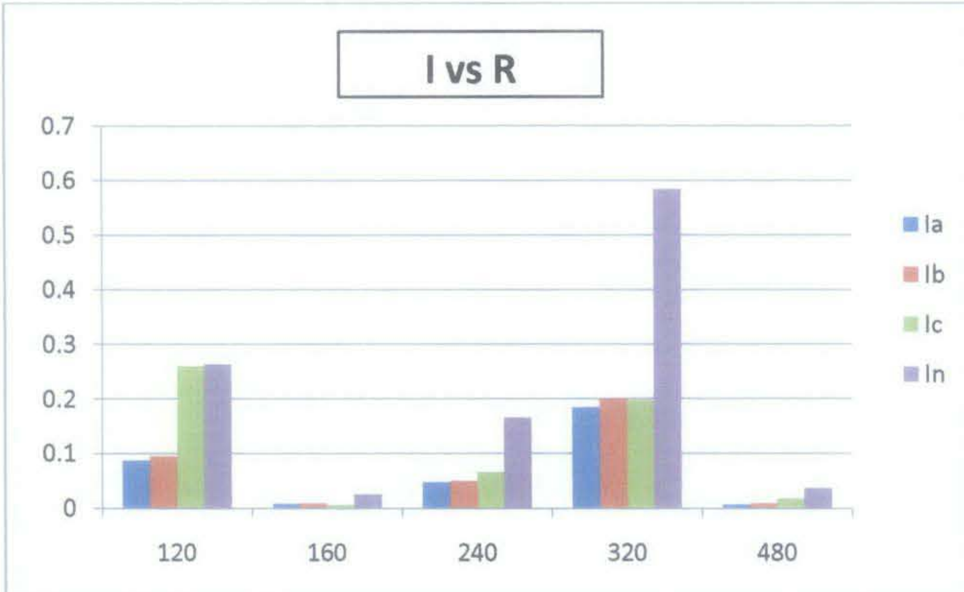

Figure 45: Graph Of Triplen Harmonics Current Vs Resistance When Single Generator Connected To Various Resistive Load

As we can see, the simulation results are a slight different than the experiment data. The voltage and current for 160 Ω and 480 Ω were too low to compare with the experiment result. This model is still in trial and error process because the correct source used in the experiment could never be identified by the software in order to give the desired outputs. This model still needs improvement and hopefully it will be done in the future.

4.2.2 Generator with Inductive Load

In single generator connected to inductive load simulation modeling, the setup and parameter used in PSCAD software will be the same as the one used in the lab scaled experiment with five different values of inductive load which consist of 0.38 H, 0.51 H, 0.76 H, 1.02 H and 1.53 H. The triplen harmonics voltage and current will only be measured at the load side. Same as the single generator connected to resistive load condition, the voltage source is modeled using third harmonics voltage sources. The voltage source is injected with third harmonics voltage magnitude, phase angle and frequency.

Table 2: Triplen Harmonics Voltage And Current When Single Generator Connected To Various Inductive Load

L (H)	Va V	Vb V	Vc V	Ia mA	Ib mA	Ic mA	In mA
0.38	0.01607	0.01755	0.02152	0.01507	0.01724	0.02223	0.0544
0.51	0.01664	0.018	0.02341	0.01078	0.01166	0.02513	0.0451
0.76	0.02136	0.02291	0.02402	0.02373	0.02975	0.03284	0.08629
1.02	0.02242	0.02366	0.0256	0.01421	0.012	0.01374	0.03987
1.53	0.01329	0.01554	0.02053	0.003362	0.003578	0.004246	0.01059

Figure 46: Graph Of Triplen Harmonics Voltage Vs Inductance When Single Generator Connected To Various Inductive Load

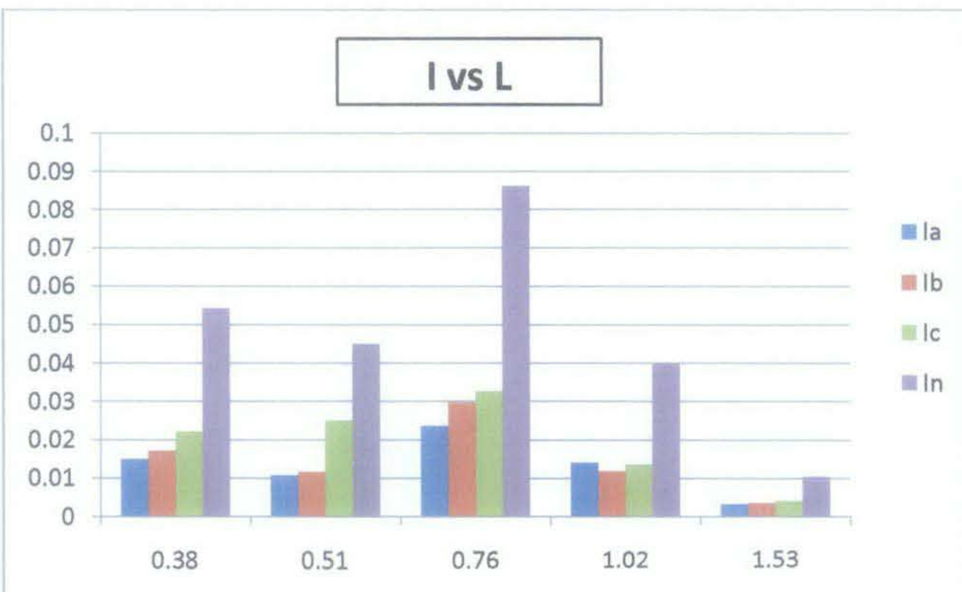

Figure 47: Graph Of Triplen Harmonics Current Vs Inductance When Single Generator Connected To Various Inductive Load

4.2.3 Generator with Resistive and Inductive Load

In single generator connected to resistive and inductive load simulation modeling, the setup and parameter used in PSCAD software will be the same as the one used in the lab scaled experiment with five different values of resistive and inductive load which consist of Case 1 = 120 Ω + 0.38 H, Case 2 = 160 Ω + 0.51 H, Case 3 = 240 Ω + 0.76 H, Case 4 = 320 Ω + 1.02 H and Case 5 = 480 Ω + 1.53 H. The triplen harmonics voltage and current will only be measured at the load side. For this simulation, the voltage source is also modeled using third ıarmonics voltage sources. The magnitude of harmonics voltages, phase angle and frequency s injected to voltage sources.

Table 3: Triplen Harmonics Voltage And Current When Single Generator Connected To Various Resistive And Inductive Load

⊦L)+(H)	R+L	Va V	Vb V	Vc V	Ia mA	Ib mA	Ic mA	In mA
e 1	120 + 0.38	0.0167	0.01958	0.01802	0.03472	0.06254	0.07348	0.1702
e 2	160 + 0.51	0.01125	0.01953	0.03021	0.07121	0.07567	0.07292	0.2187
e 3	240 + 0.76	0.01747	0.01987	0.01722	0.0444	0.04613	0.05529	0.1458
e 4	320 + 1.02	0.000325	0.002431	0.004127	0.000325	0.001735	0.002406	0.004453
e 5	480 + 1.53	0.003819	0.007658	0.01004	0.001484	0.002011	0.002256	0.005596

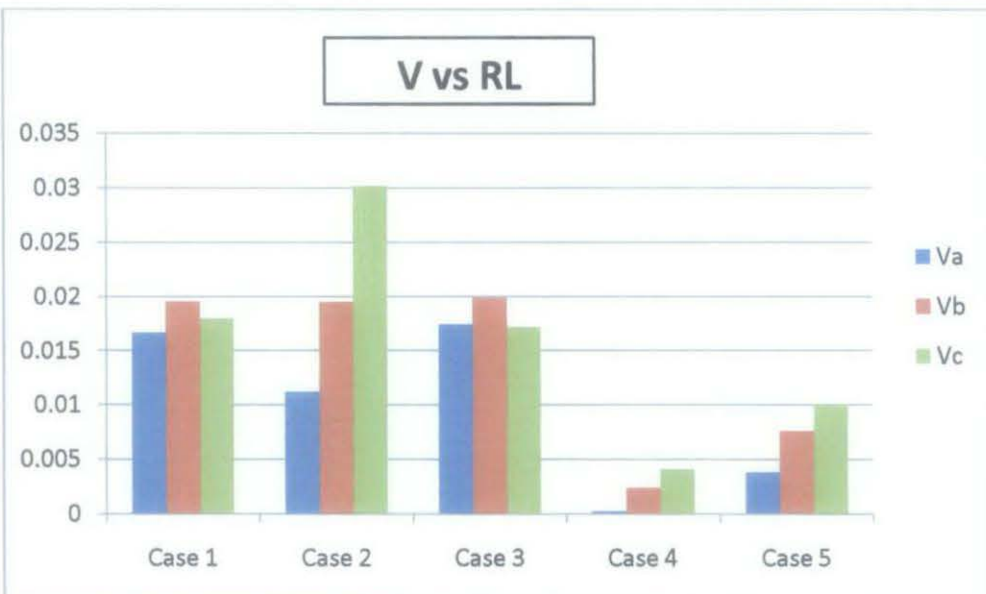

Figure 48: Graph Of Triplen Harmonics Voltage Vs Resistance + Inductance When Single Generator Connected To Various Resistive And Inductive Load

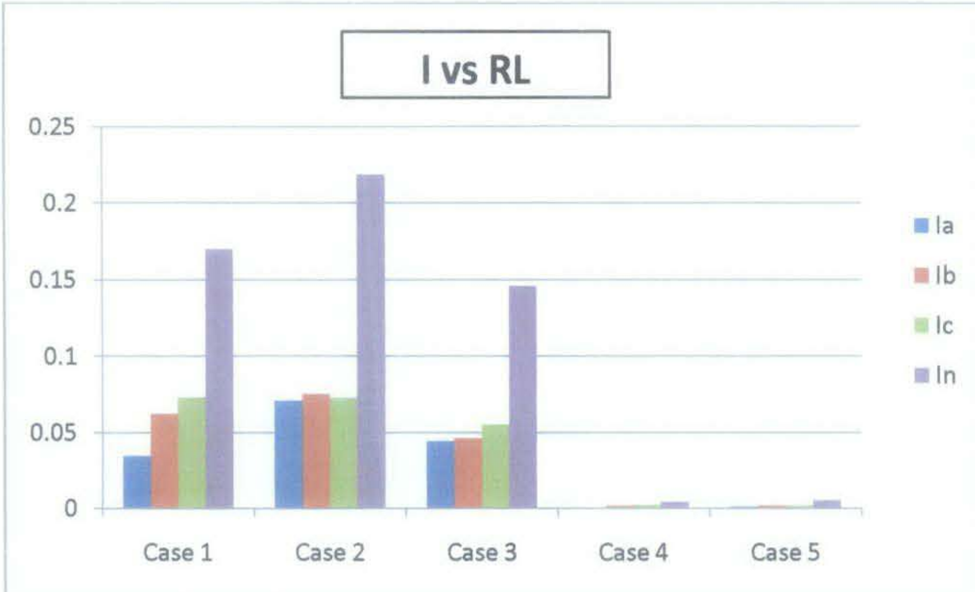

Figure 49: Graph Of Triplen Harmonics Current Vs Resistance + Inductance When Single Generator Connected To Various Resistive And Inductive Load

As we can see, the simulation results are a slight different than the experiment data. The voltage and current for Case 4 and Case 5 were too low for comparison with the result obtained during the experiment. This model is still in trial and error process because the correct source used in the experiment could never be identified by the software in order to give the desired outputs. This model still needs improvement and hopefully it will be done in the future.

CHAPTER 5

RECOMMENDATIONS AND CONCLUSION

.1 Recommendations

'he study on the effect of cable capacitance on the characteristics or behaviours of triplen iarmonics produced by synchronous generator is very essential as this research can provide a 'ery important input to mitigate method in reducing harmonics in power system. How triplen iarmonics affect the power system is a very important study that need to be done because the mly way to reduce harmonics is by studying their sources, return path, where they circulating ınd their impacts to line voltages and currents. Studying harmonics behaviour is not an easy ask as it needs knowledge, proper software and high technology equipment. I highly ecommend the university to add two or three more equipment in the lab for measuring the resence of harmonics in electrical circuit. For further thorough analysis regarding the effect of cable capacitance on triplen harmonics produced by synchronous generator, it is ecommended to do researches that include more capacitor connected to the phase wire. This s to make sure that the increasing trend of third harmonics currents flowing into capacitor is ccurate and fully proved. Besides, a long period of studies needs to be considered which will nclude another part in the experiment which consist of single generator connected parallel to he grid and two generator connected in parallel so that a proper standards can be performed ınd implied in the industrial sector. This can provide us more understanding on the effect of :able capacitance on triplen harmonics current produced by synchronous generator.

.2 Conclusion

From the experiment data that have been gathered and analyse, we can conclude that capacitor does attract triplen harmonics currents. The magnitude of triplen harmonics currents generated by single generator that flow into capacitor increased when the value of capacitor increased. The capacitor in the circuit represents the cable capacitance. The higher the value of capacitor means that the longer the transmission line. From the experiment we can observed that the magnitude of the triplen harmonics current at capacitor side is very small because the value of capacitor used is small. From the experiment also we can observed that when we increased the load impedance, balanced resistive load or balanced inductive load, the triplen harmonics currents that present in the system will decrease. The neutral currents magnitude is very high when inductive load is connected because triplen harmonics currents are additive in neutral. The findings that can be concluded from the experiment are the amount of triplen harmonics currents that flow into the capacitor. After the experiment has been done, the data gathered was used to model the circuit in PSCAD. The purpose is to find the right 3 phase source for the simulation. The modelling part is still in trial and error mode because the author couldn't find the right source to use.

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ɩPPENDIX

1. Synchronous motor or generator rating (LabVolt EMS 8507-0A)
    - 1500 r/min
    - 240/415 Volts AC
    - 50 Hz
    - 240 VDC
    - Motor (2 kW, 0.50 Amps DC)
    - Generator (1.5 kVA, 0.48 Amps DC)
2. DC Motor or generator rating
    - Motor (2 kW, 1500 r/min, 240V, 11A)
    - Generator (1.5 kW, 1500 r/min, 240V, 0.2A)
3. Field rheostat rating
    - 600 Ohm
    - 225W
4. Three phase Transformer rating
    - 250 VA
    - 415/415 V
    - 0.8 A
    - 50 Hz
5. Resistive load rating
    - 1140 W
    - 240 V AC/DC
    - Accuracy +- 5%
6. Tools used :
    - Fluke Power Analyzer
    - Generator
    - Three phase Transformer
    - Resistive load

\PPENDIX II: Lab Experiment Result

;ingle Generator Connected to Capacitor (as cable capacitance) and Balanced Resistive .oad

<u>Resistive Load 120 Ohm, Capacitor 0.66 uF</u>

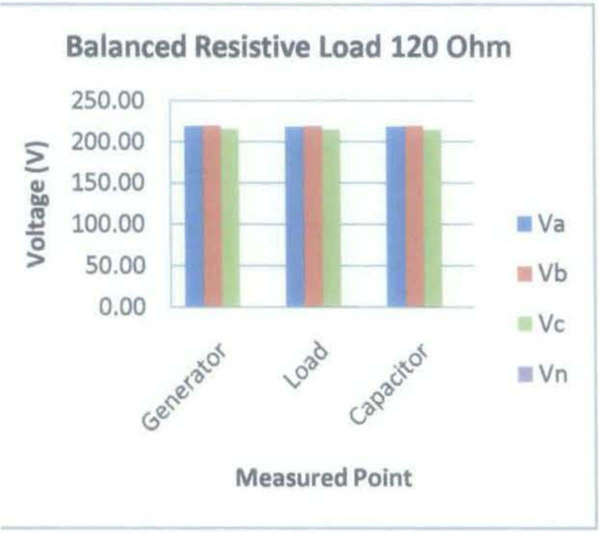

Figure 50: Fundamental voltage measured at various points with balanced resistive load 120 Ohm

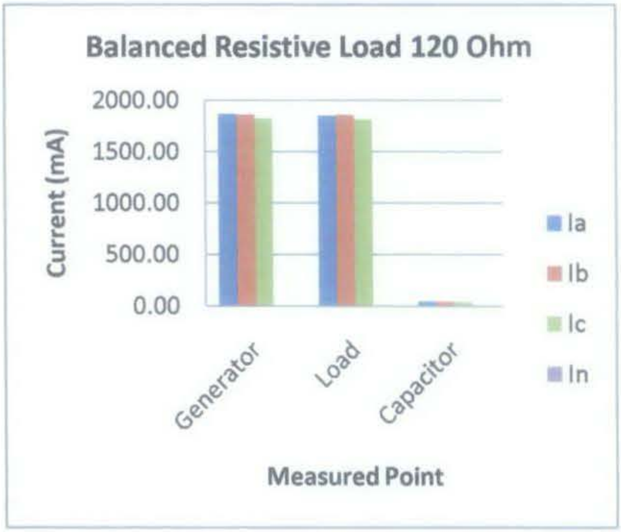

Figure 51: Fundamental current measured at various points with balanced resistive load 120 Ohm

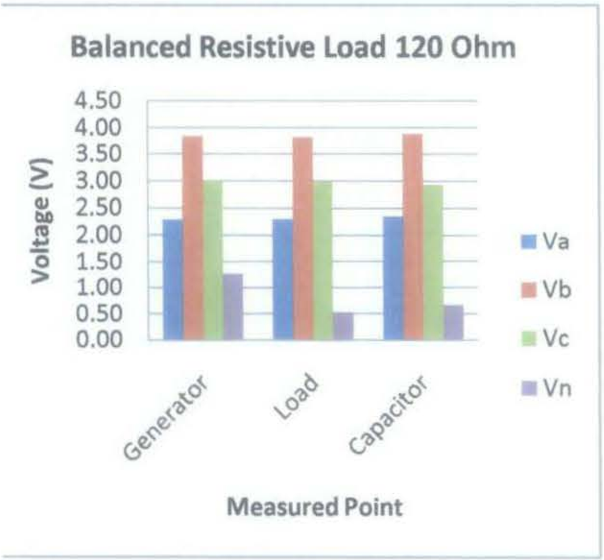

Figure 52: 3rd harmonic voltage measured at various points with balanced resistive load 120 Ohm

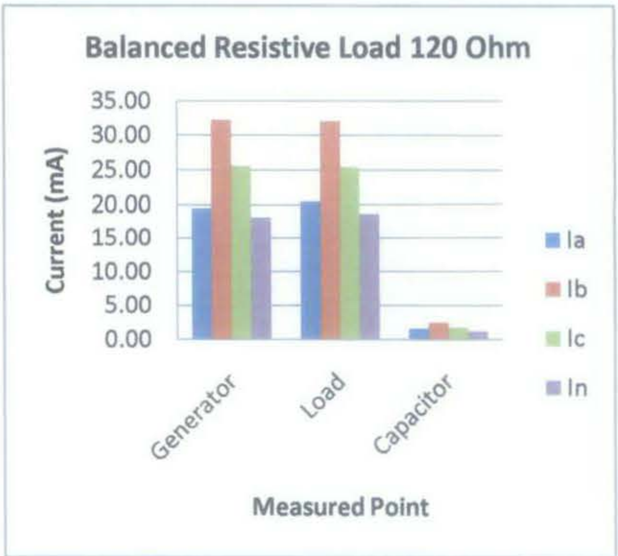

Figure 53: 3rd harmonic current measured at various points with balanced resistive load 120 Ohm

Resistive Load 160 Ohm Capacitor 0.66 uF

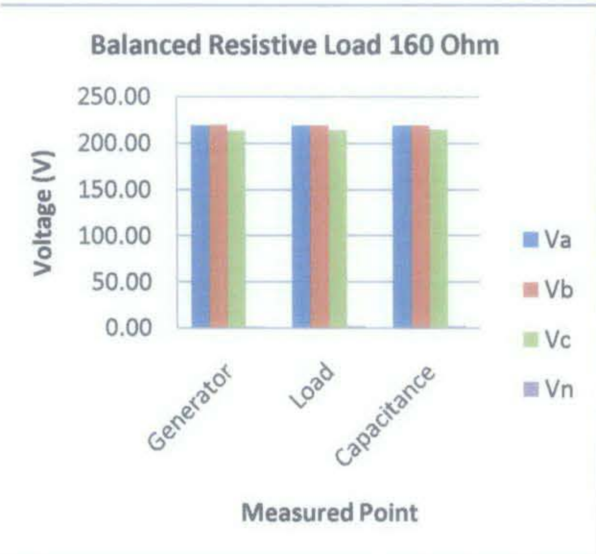

Figure 54: Fundamental voltage measured at various points with balanced resistive load 160 Ohm

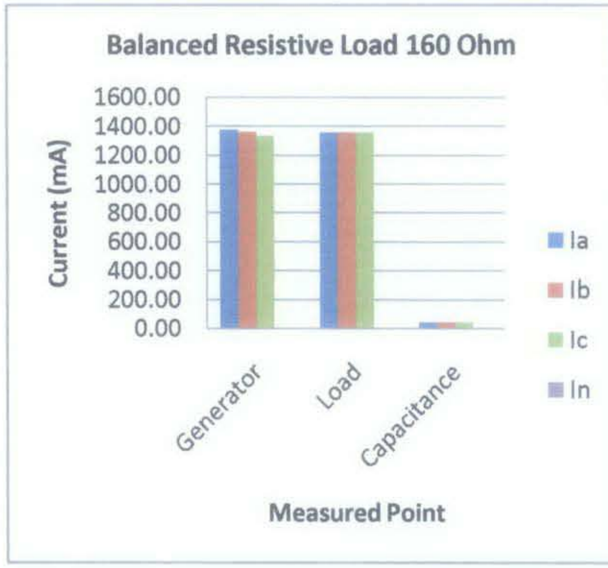

Figure 55: Fundamental current measured at various points with balanced resistive load 160 Ohm

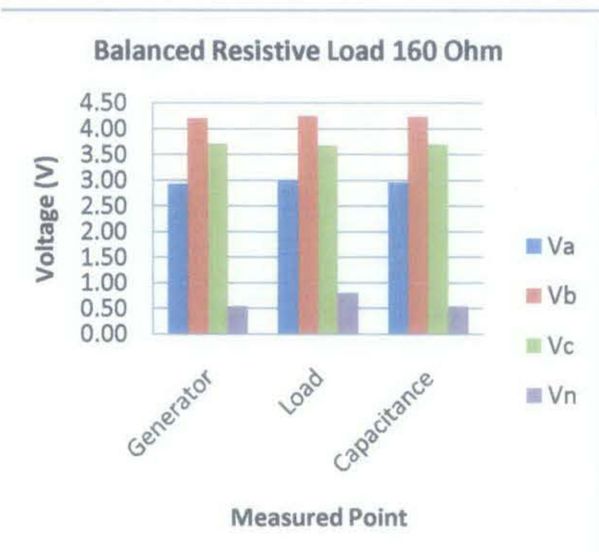

Figure 56: 3rd harmonic voltage measured at various points with balanced resistive load 160 Ohm

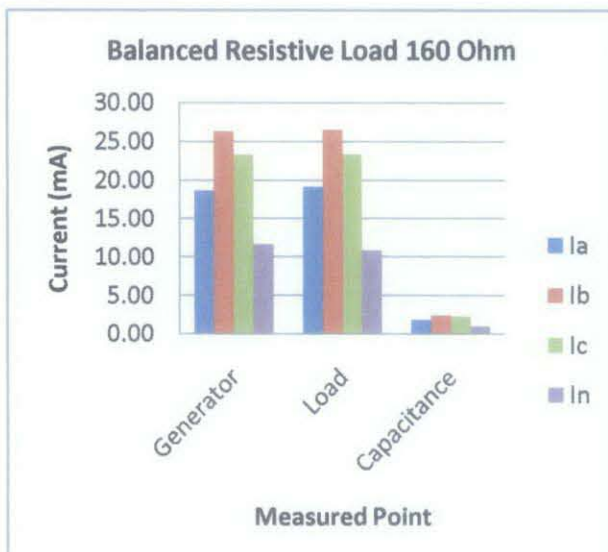

Figure 57: 3rd harmonic current measured at various points with balanced resistive load 160 Ohm

Resistive Load 240 Ohm Capacitor 0.66 uF

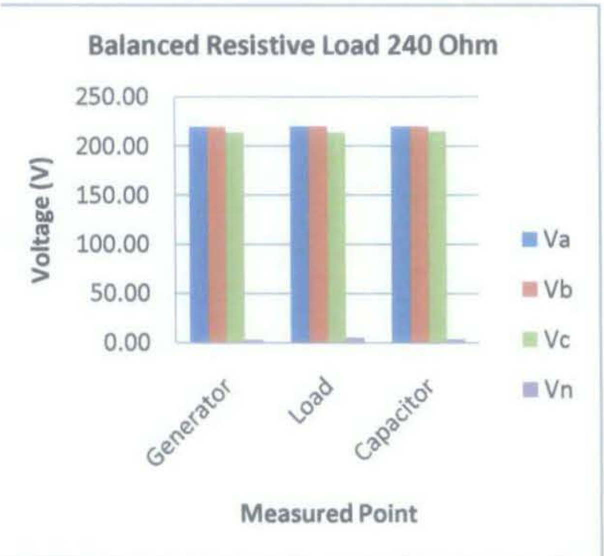

Figure 58: Fundamental voltage measured at various points with balanced resistive load 240 Ohm

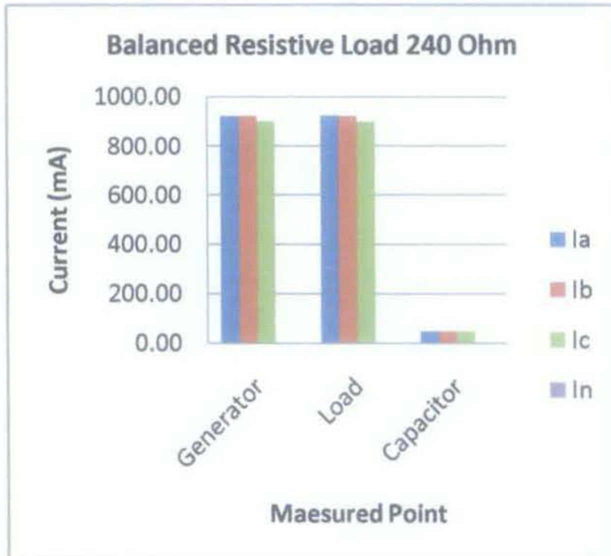

Figure 59: Fundamental current measured at various points with balanced resistive load 240 Ohm

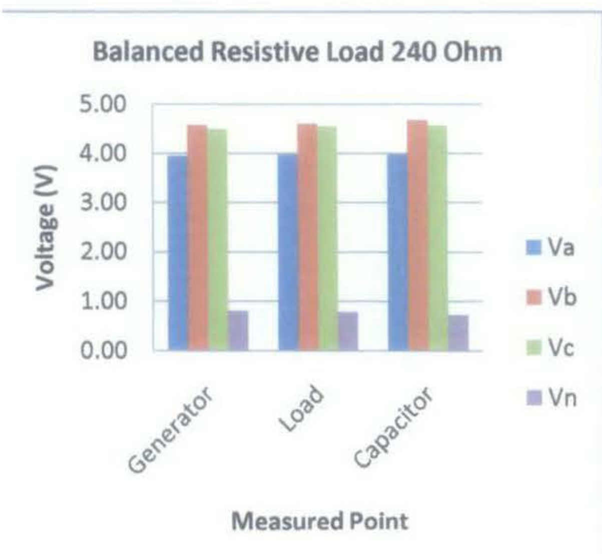

Figure 60: 3rd harmonic voltage measured at various points with balanced resistive load 240 Ohm

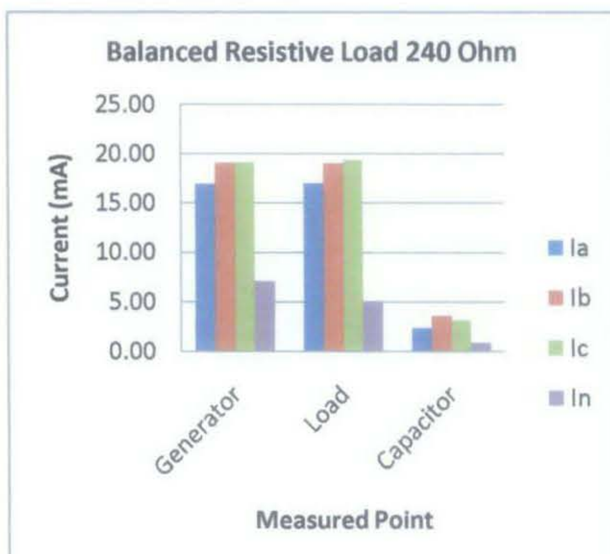

Figure 61: 3rd harmonic current measured at various points with balanced resistive load 240 Ohm

₹esistive Load 320 Ohm Capacitor 0.66 uF

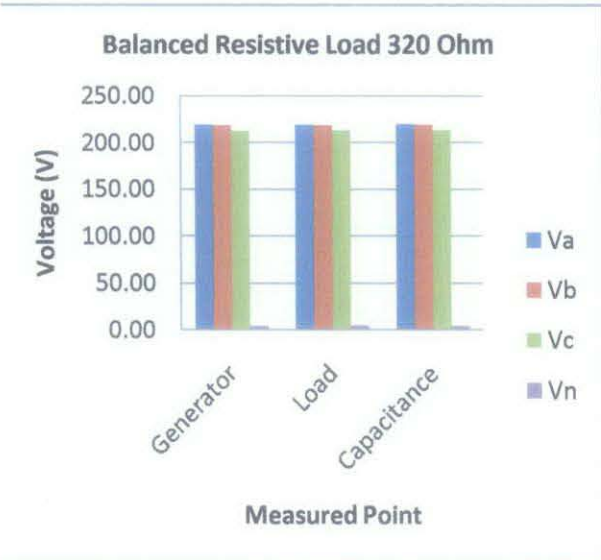

Figure 62: Fundamental voltage measured at various points with balanced resistive load 320 Ohm

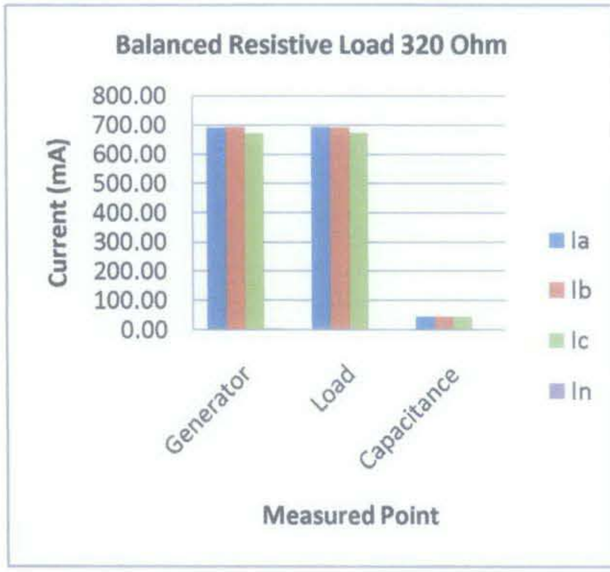

Figure 63: Fundamental current measured at various points with balanced resistive load 320 Ohm

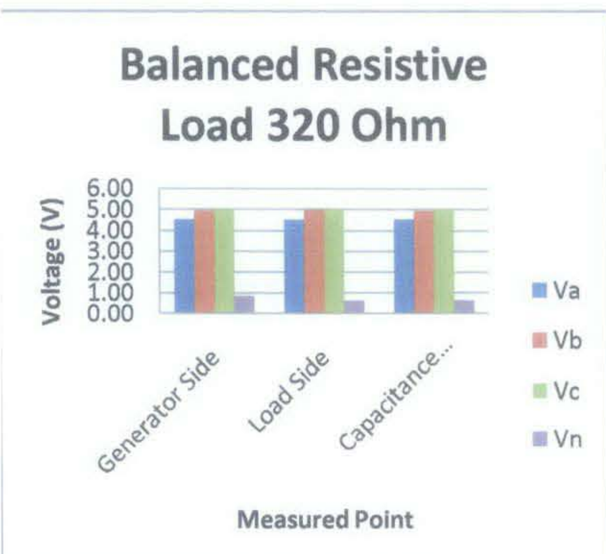

Figure 64: 3rd harmonic voltage measured at various points with balanced resistive load 320 Ohm

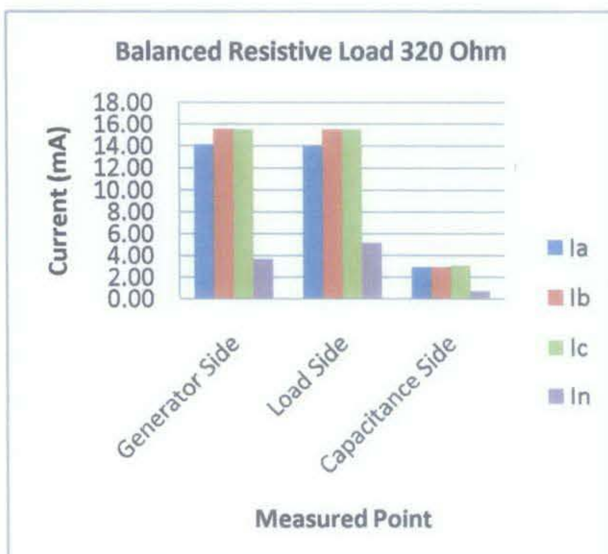

Figure 65: 3rd harmonic current measured at various points with balanced resistive load 320 Ohm

Resistive Load 120 Ohm Capacitor 1.33 uF

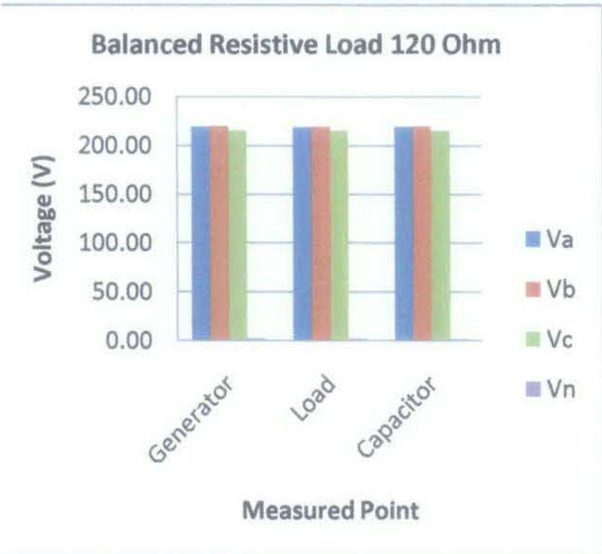

Figure 66: Fundamental voltage measured at various points with balanced resistive load 120 Ohm

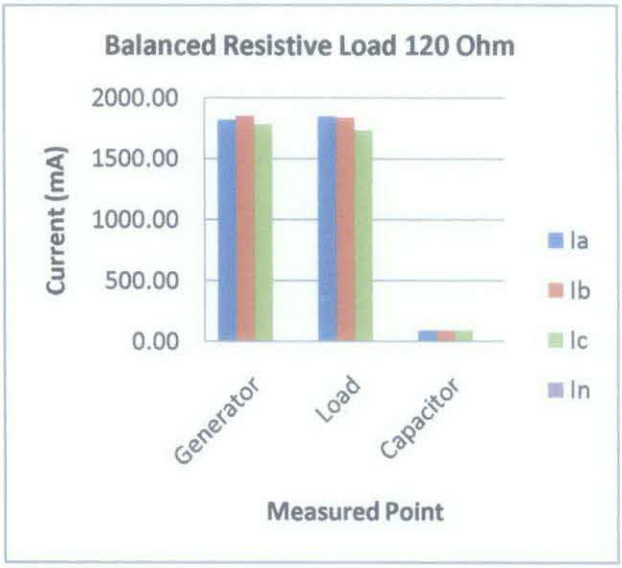

Figure 67: Fundamental current measured at various points with balanced resistive load 120 Ohm

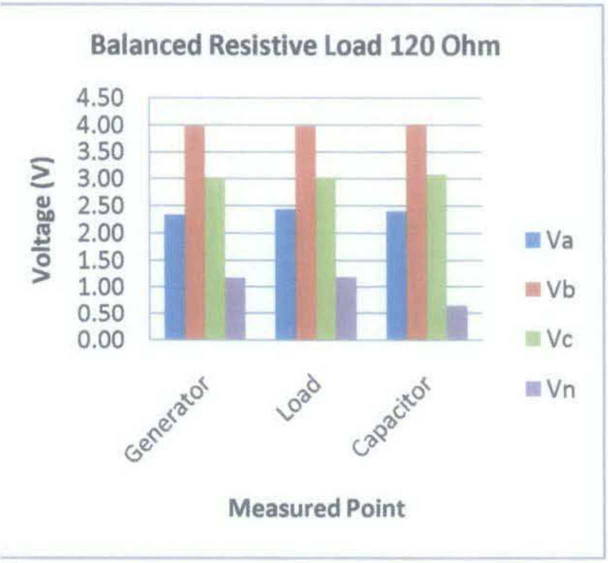

Figure 68: 3rd harmonic voltage measured at various points with balanced resistive load 120 Ohm

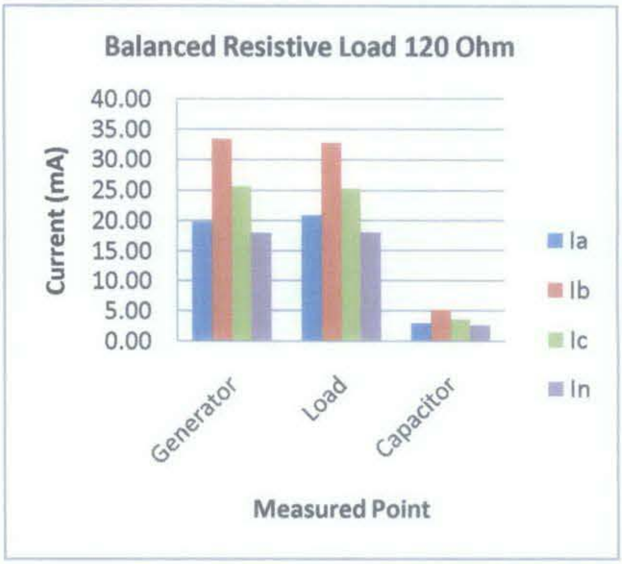

Figure 69: 3rd harmonic current measured at various points with balanced resistive load 120 Ohm

₹esistive Load 160 Ohm Capacitor 1.33 uF

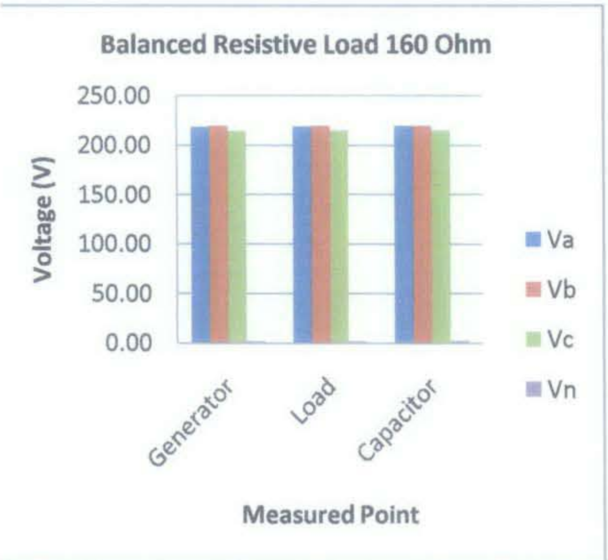

Figure 70: Fundamental voltage measured at various points with balanced resistive load 160 Ohm

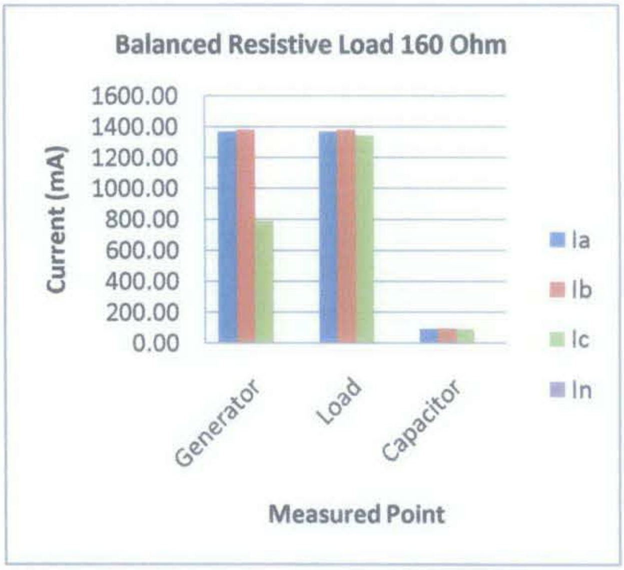

Figure 71: Fundamental current measured at various points with balanced resistive load 160 Ohm

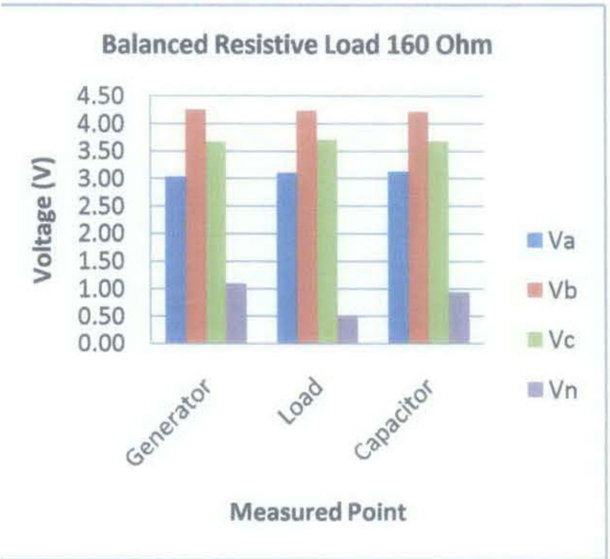

Figure 72: 3rd harmonic voltage measured at various points with balanced resistive load 160 Ohm

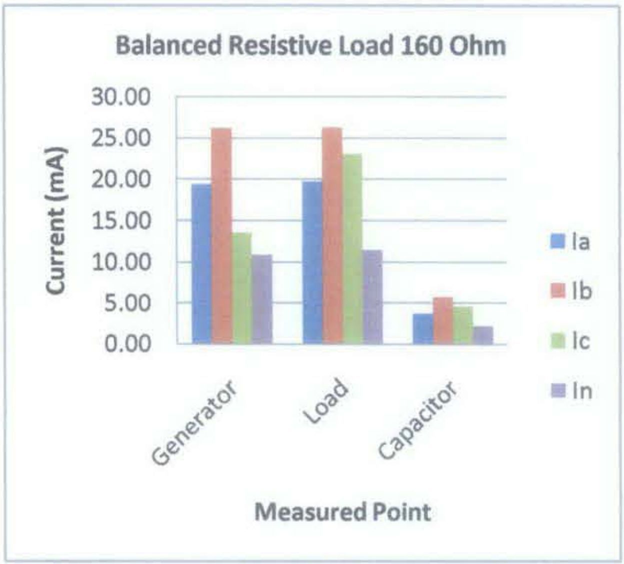

Figure 73: 3rd harmonic current measured at various points with balanced resistive load 160 Ohm

₹esistive Load 240 Ohm Capacitor 1.33 uF

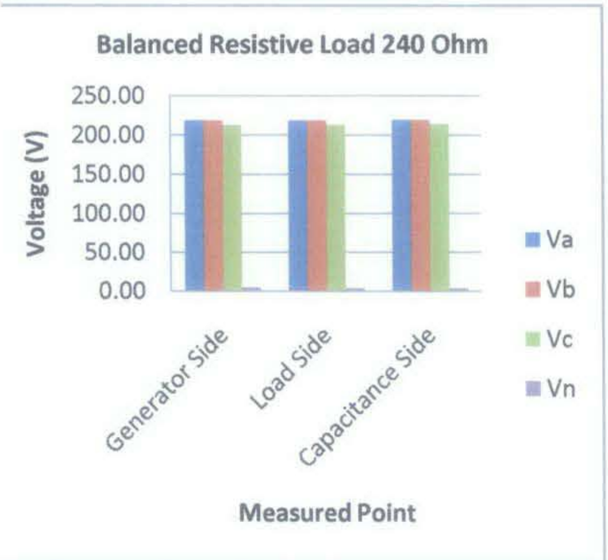

Figure 74: Fundamental voltage measured at various points with balanced resistive load 240 Ohm

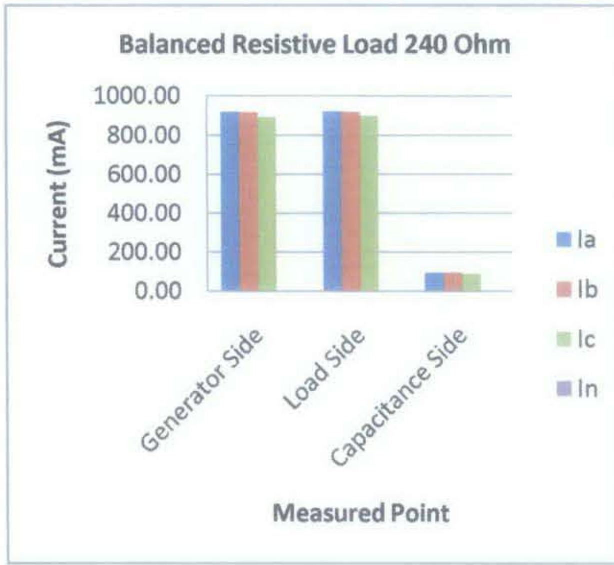

Figure 75: Fundamental current measured at various points with balanced resistive load 240 Ohm

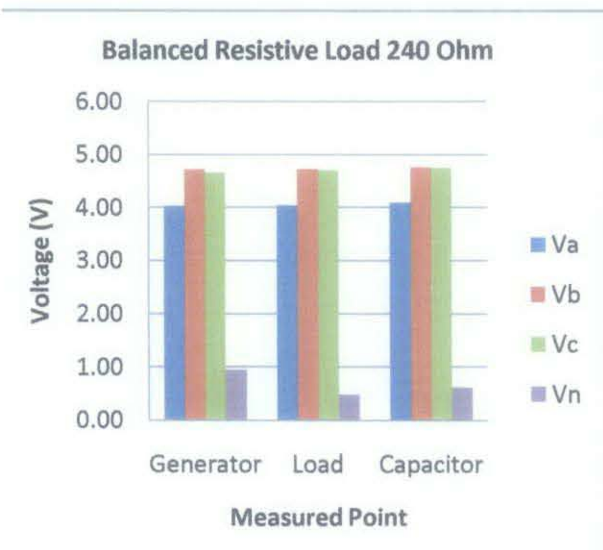

Figure 76: 3rd harmonic voltage measured at various points with balanced resistive load 240 Ohm

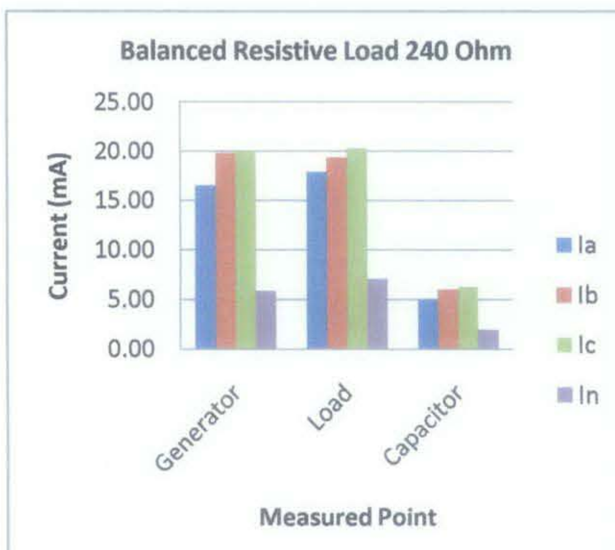

Figure 77: 3rd harmonic current measured at various points with balanced resistive load 240 Ohm

Resistive Load 320 Ohm Capacitor 1.33 uF

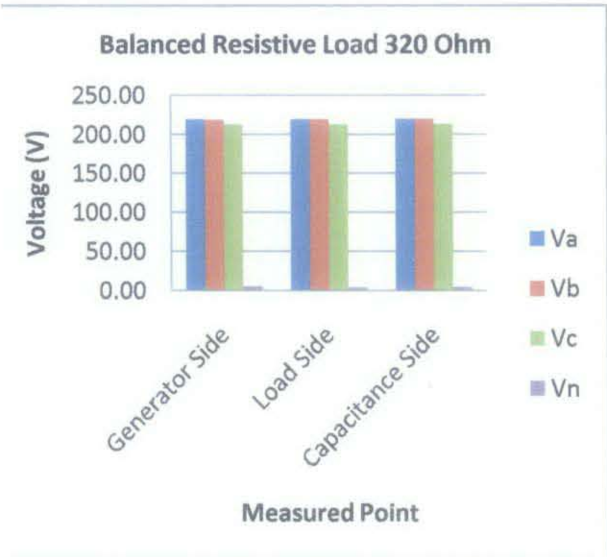

Figure 77: Fundamental voltage measured at various points with balanced resistive load 320 Ohm

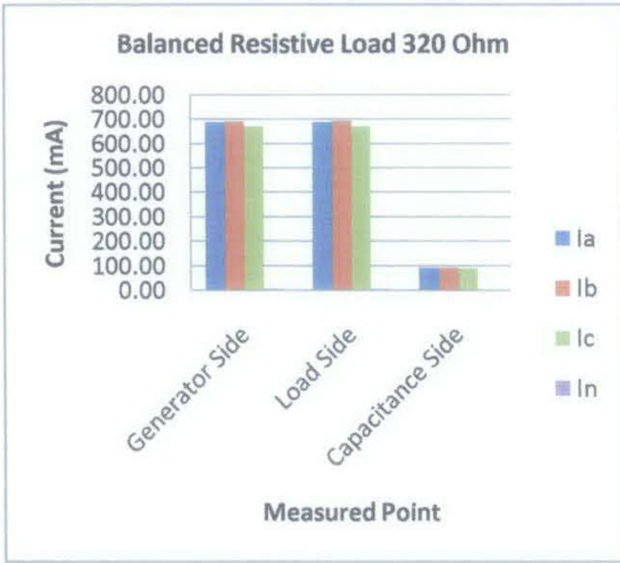

Figure 78: Fundamental current measured at various points with balanced resistive load 320 Ohm

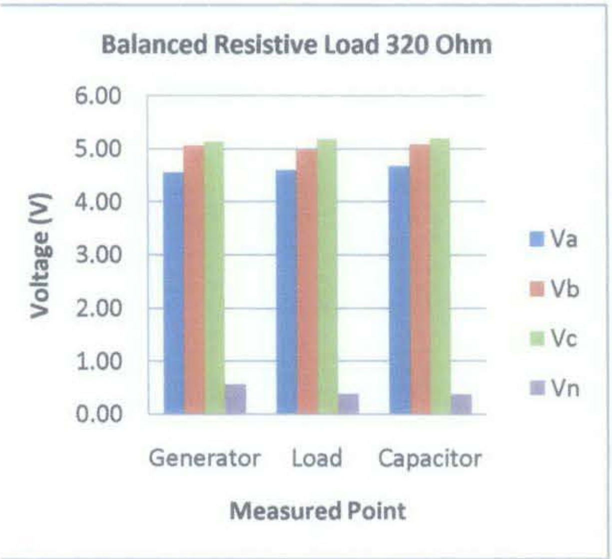

Figure 79: 3rd harmonic voltage measured at various points with balanced resistive load 320 Ohm

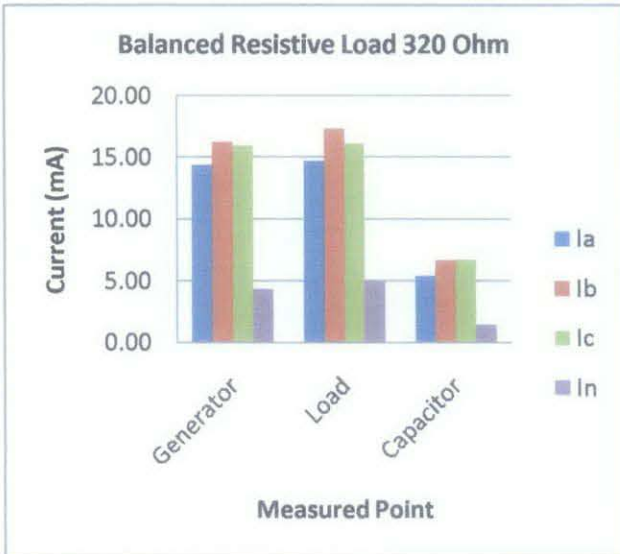

Figure 80: 3rd harmonic current measured at various points with balanced resistive load 320 Ohm

Resistive Load 480 Ohm Capacitor 1.33 uF

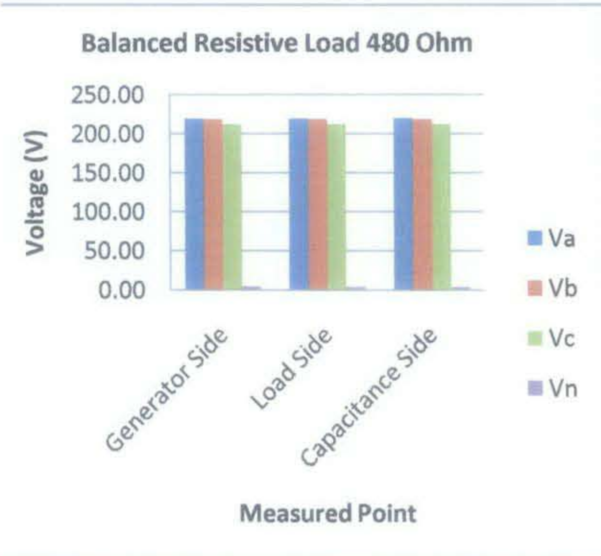

Figure 81: Fundamental voltage measured at various points with balanced resistive load 480 Ohm

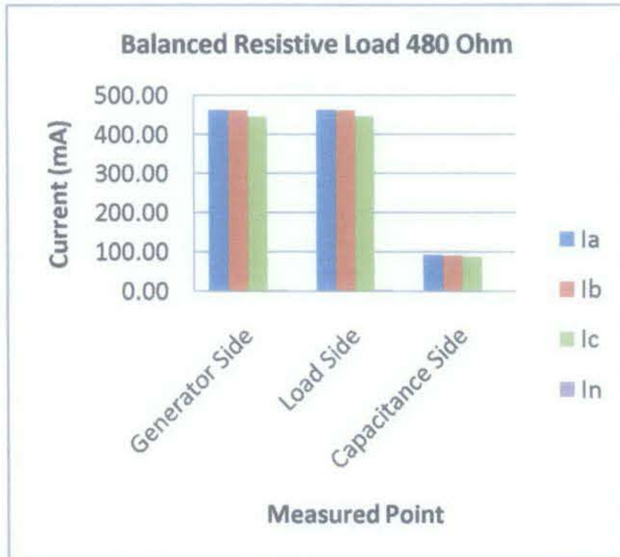

Figure 82: Fundamental current measured at various points with balanced resistive load 480 Ohm

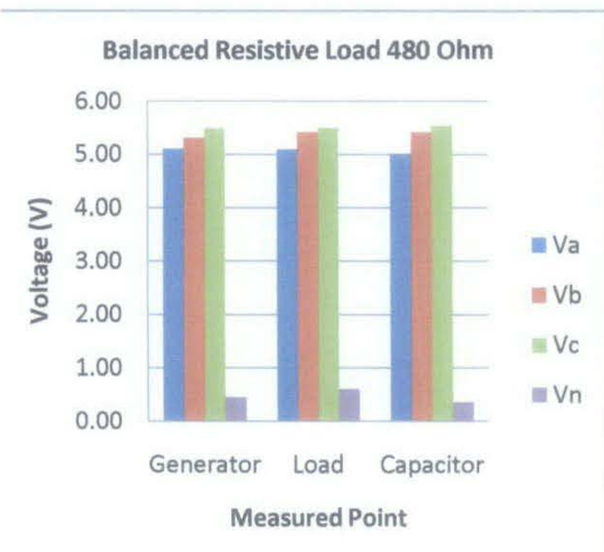

Figure 83: 3rd harmonic voltage measured at various points with balanced resistive load 480 Ohm

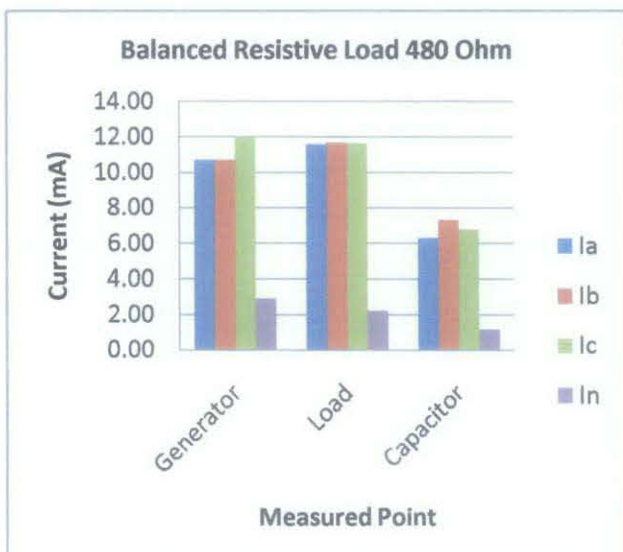

Figure 84: 3rd harmonic current measured at various points with balanced resistive load 480 Ohm

Resistive Load 120 Ohm Capacitor 2.65 uF

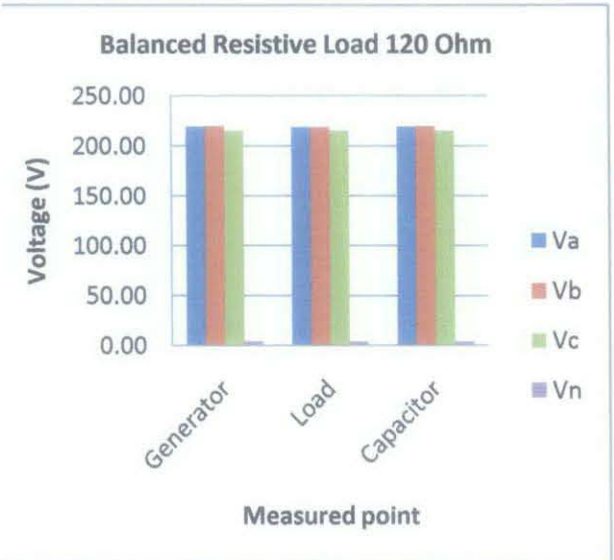

Figure 85: Fundamental voltage measured at various points with balanced resistive load 120 Ohm

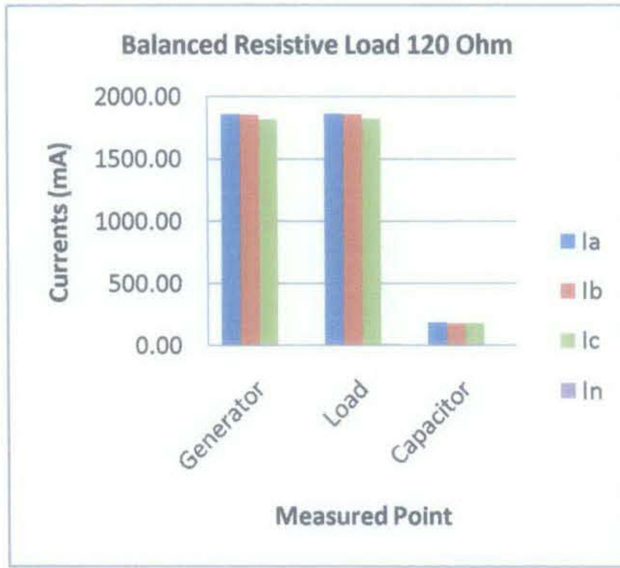

Figure 86: Fundamental current measured at various points with balanced resistive load 120Ohm

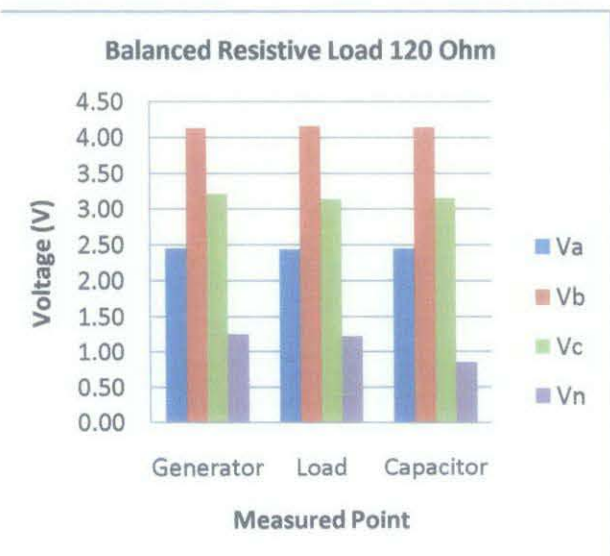

Figure 87: 3rd harmonic voltage measured at various points with balanced resistive load 120 Ohm

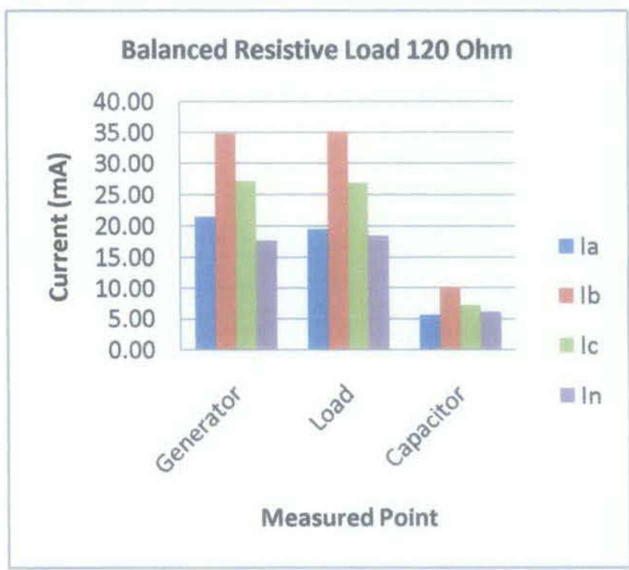

Figure 88: 3rd harmonic current measured at various points with balanced resistive load 120 Ohm

ƚesistive Load 160 Ohm Capacitor 2.65 uF

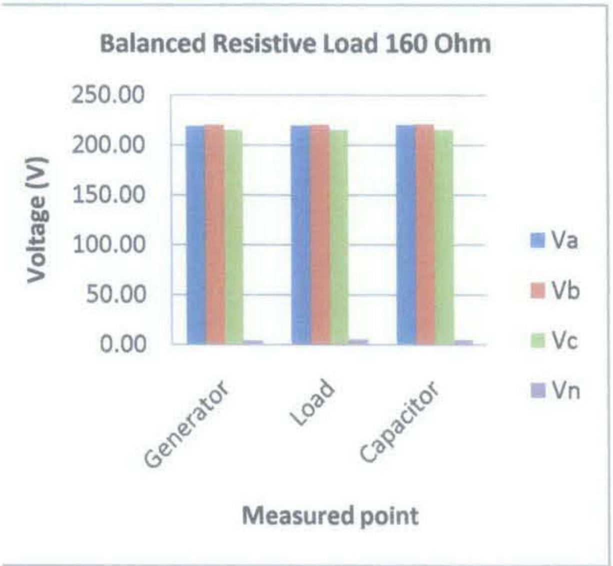

Figure 89: Fundamental voltage measured at various points with balanced resistive load 160 Ohm

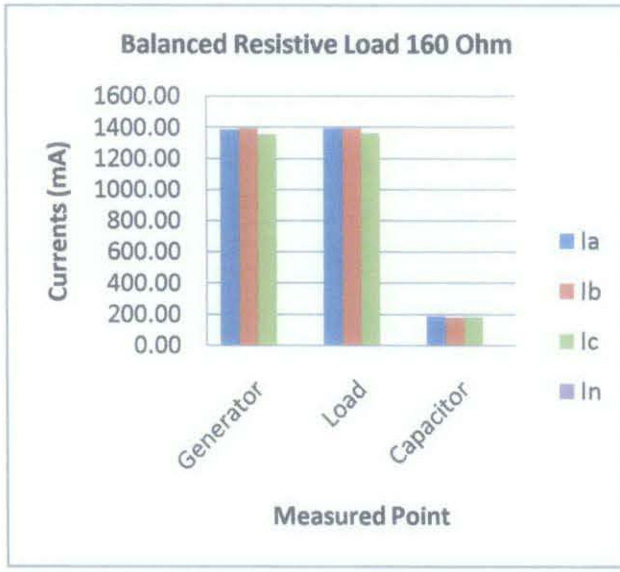

Figure 90: Fundamental current measured at various points with balanced resistive load 160 Ohm

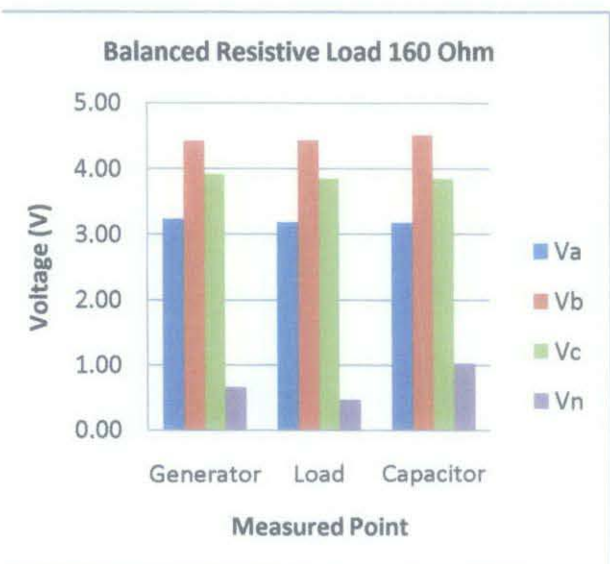

Figure 91: 3rd harmonic voltage measured at various points with balanced resistive load 160 Ohm

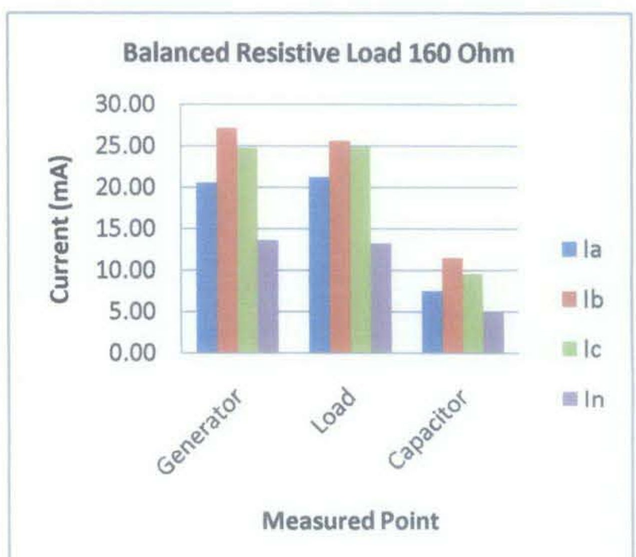

Figure 92: 3rd harmonic current measured at various points with balanced resistive load 160 Ohm

Resistive Load 240 Ohm Capacitor 2.65 uF

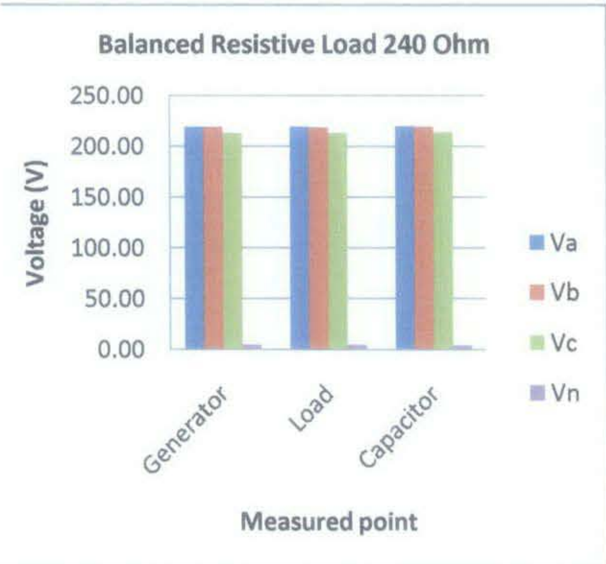

Figure 93: Fundamental voltage measured at various points with balanced resistive load 240 Ohm

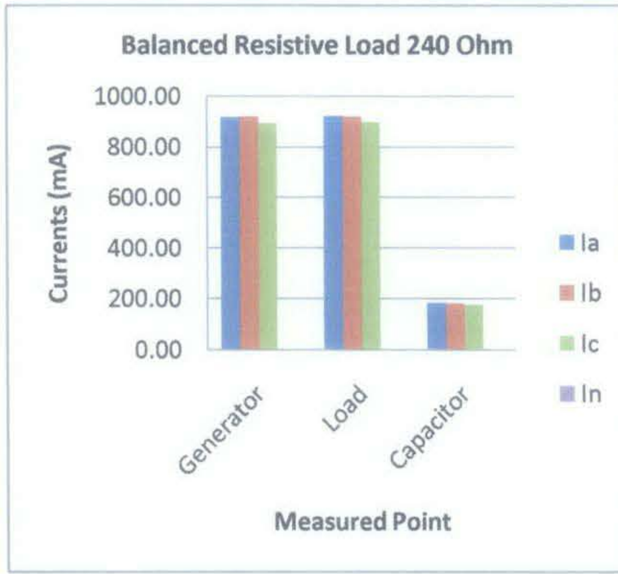

Figure 94: Fundamental current measured at various points with balanced resistive load 240 Ohm

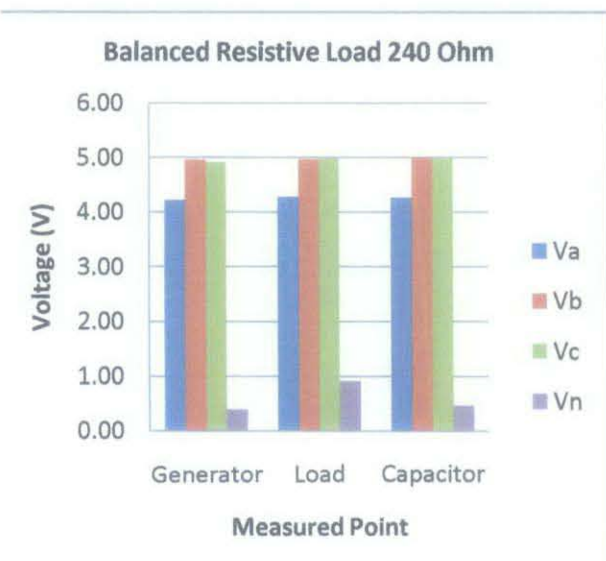

Figure 95: 3rd harmonic voltage measured at various points with balanced resistive load 240 Ohm

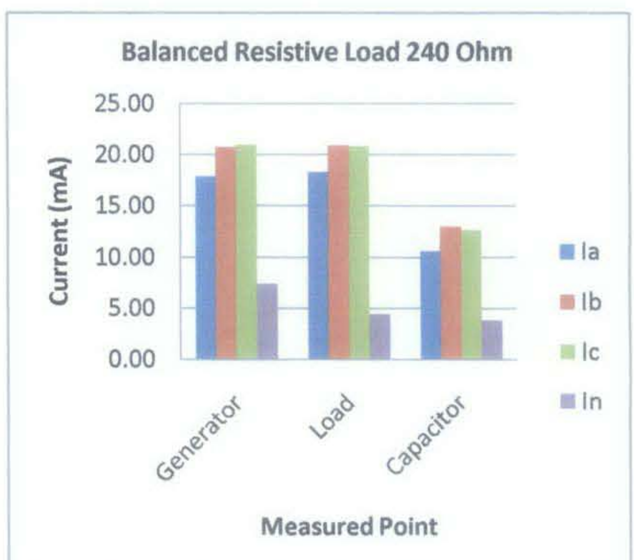

Figure 96: 3rd harmonic current measured at various points with balanced resistive load 240 Ohm

Resistive Load 320 Ohm Capacitor 2.65 uF

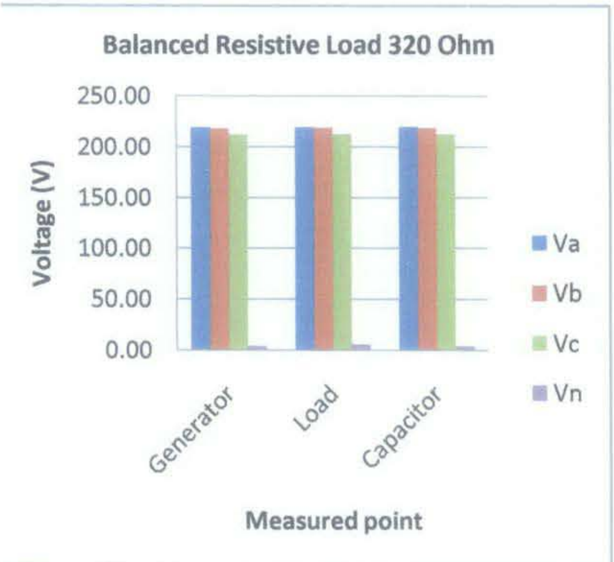

Figure 97: Fundamental voltage measured at various points with balanced resistive load 320 Ohm

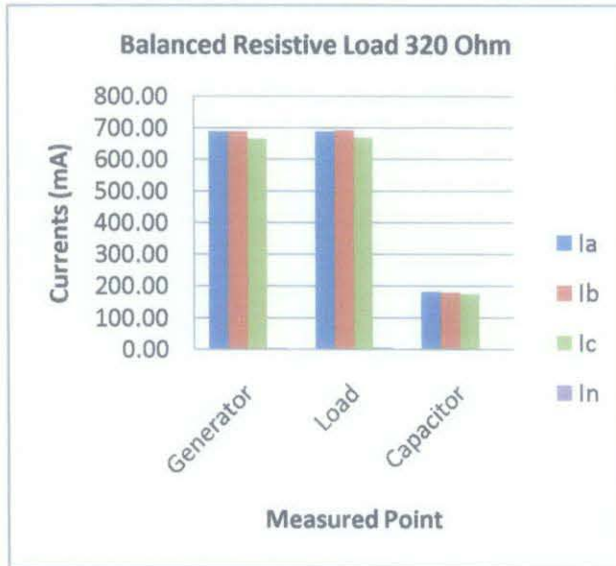

Figure 98: Fundamental current measured at various points with balanced resistive load 320 Ohm

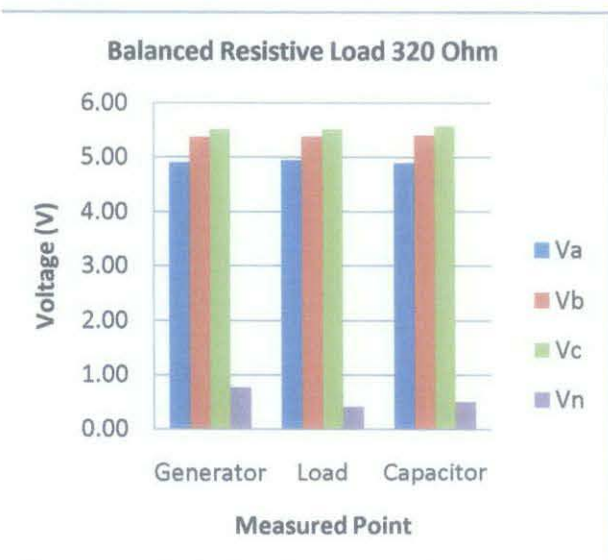

Figure 99: 3rd harmonic voltage measured at various points with balanced resistive load 320 Ohm

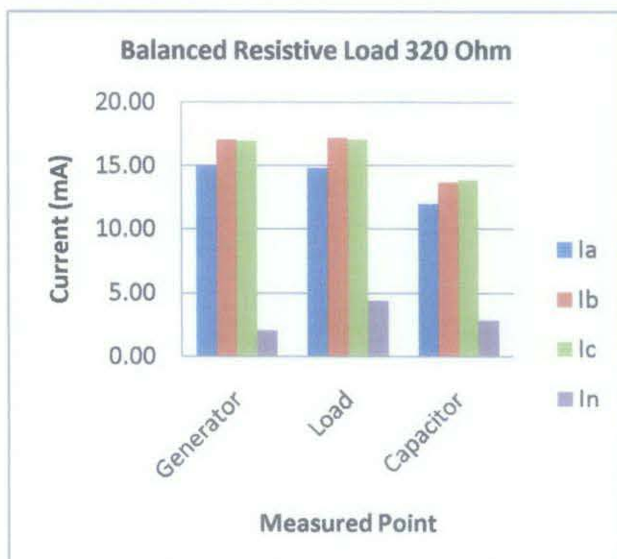

Figure 100: 3rd harmonic current measured at various points with balanced resistive load 320 Ohm

Resistive Load 480 Ohm Capacitor 2.65 uF

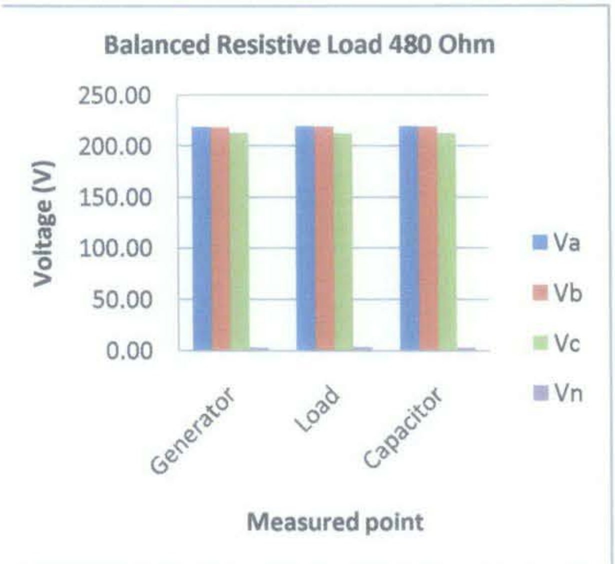

Figure 101: Fundamental voltage measured at various points with balanced resistive load 480 Ohm

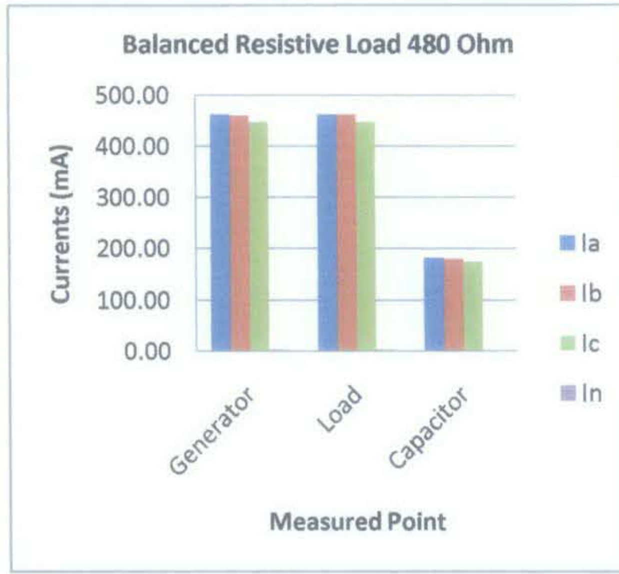

Figure 102: Fundamental current measured at various points with balanced resistive load 480 Ohm

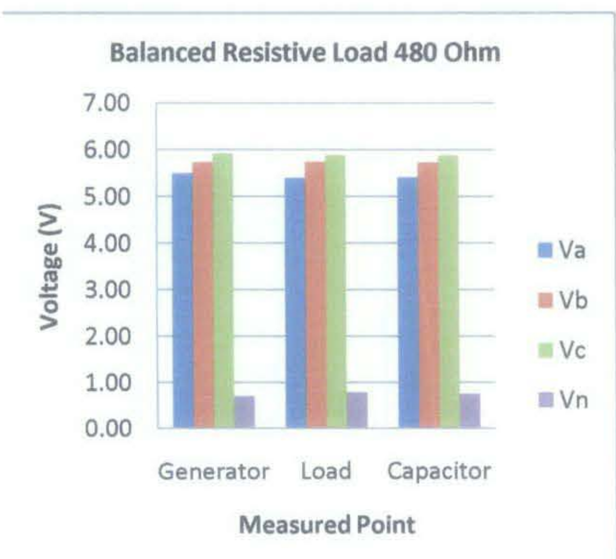

Figure 103: 3rd harmonic voltage measured at various points with balanced resistive load 480 Ohm

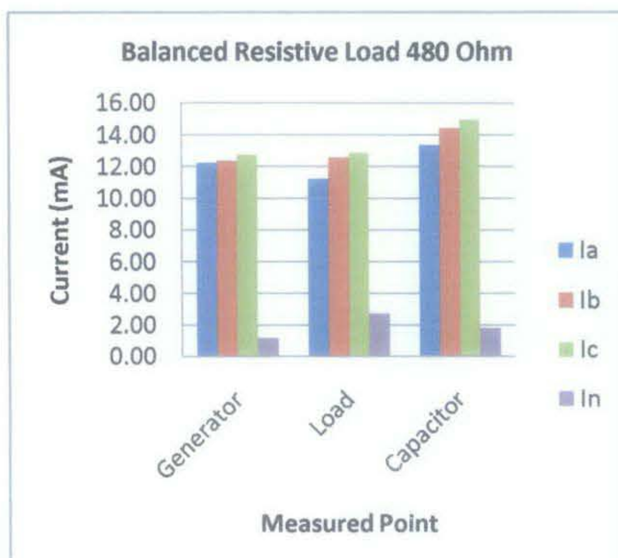

Figure 104: 3rd harmonic current measured at various points with balanced resistive load 480 Ohm

ingle Generator Connected to Capacitor (as cable capacitance) and Balanced Inductive
Load

nductive Load 0.38 H Capacitor 0.66 uF

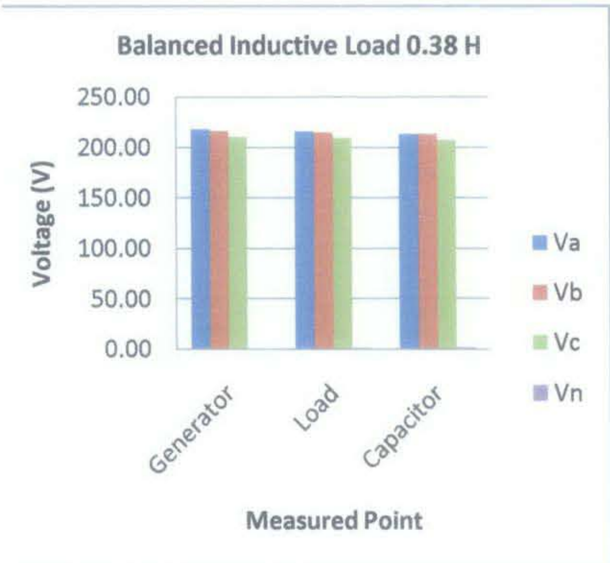

Figure 105: Fundamental voltage measured at various points with balanced inductive load 0.38 H

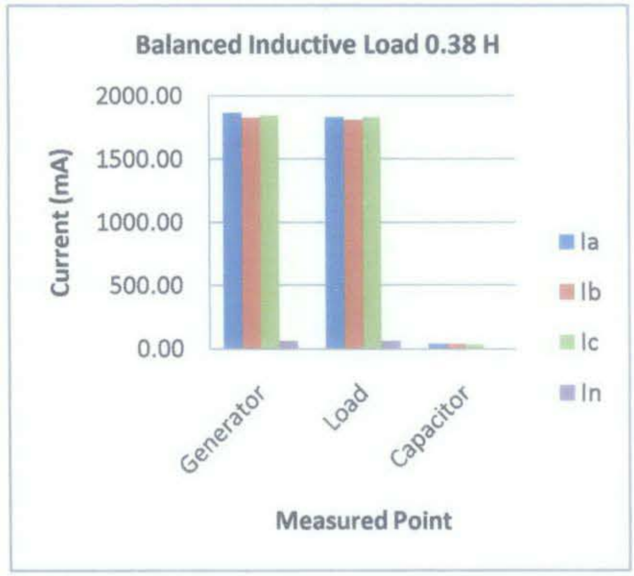

Figure 106: Fundamental current measured at various points with balanced inductive load 0.38 H

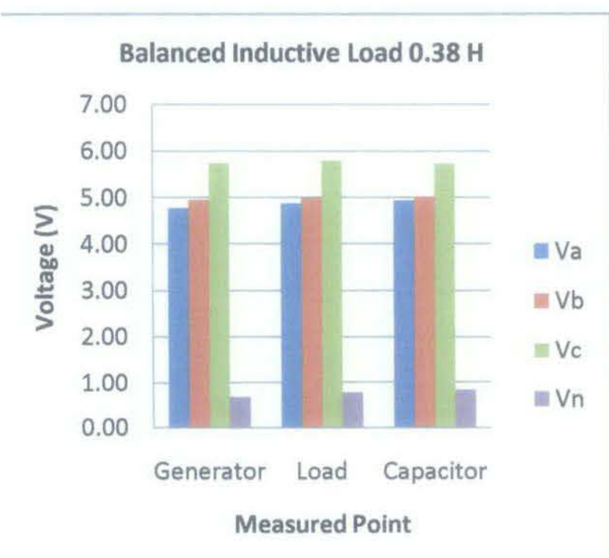

Figure 107: 3rd harmonic voltage measured at various points with balanced inductive load 0.38 H

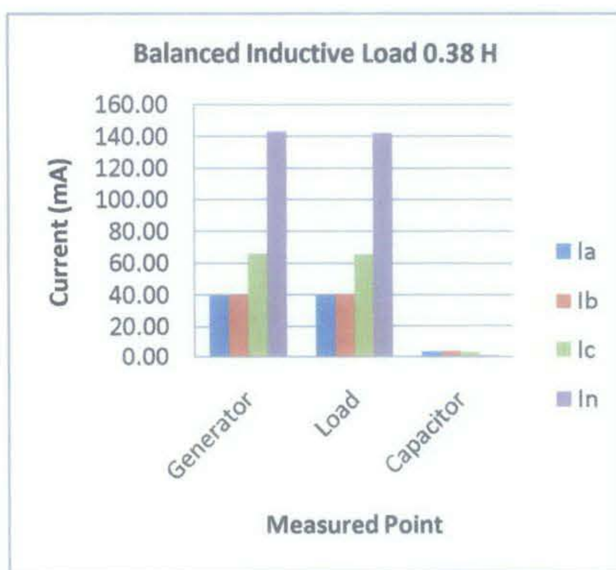

Figure 108: 3rd harmonic current measured at various points with balanced inductive load 0.38 H

nductive Load 0.51 H Capacitor 0.66 uF

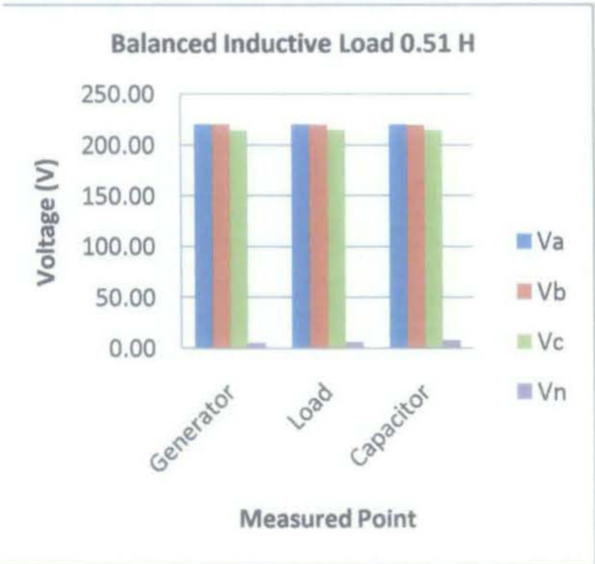

Figure 109: Fundamental voltage measured at various points with balanced inductive load 0.51 H

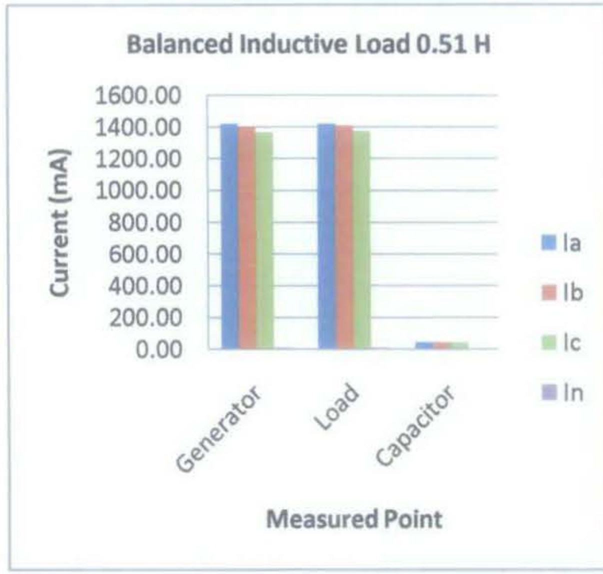

Figure 110: Fundamental current measured at various points with balanced inductive load 0.51 H

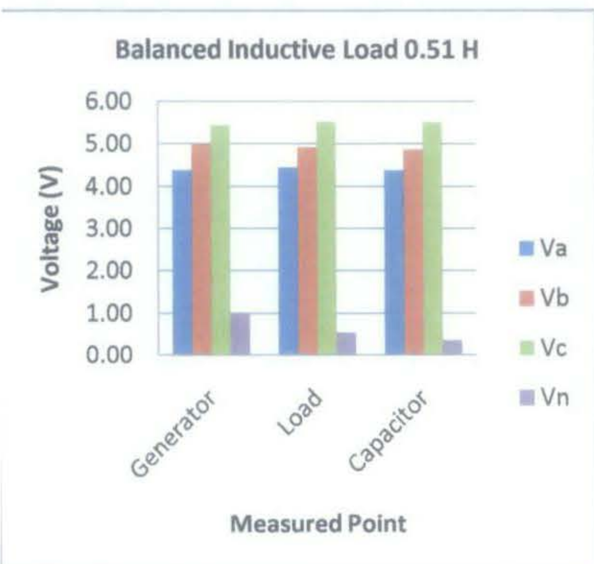

Figure 111: 3rd harmonic voltage measured at various points with balanced inductive load 0.51 H

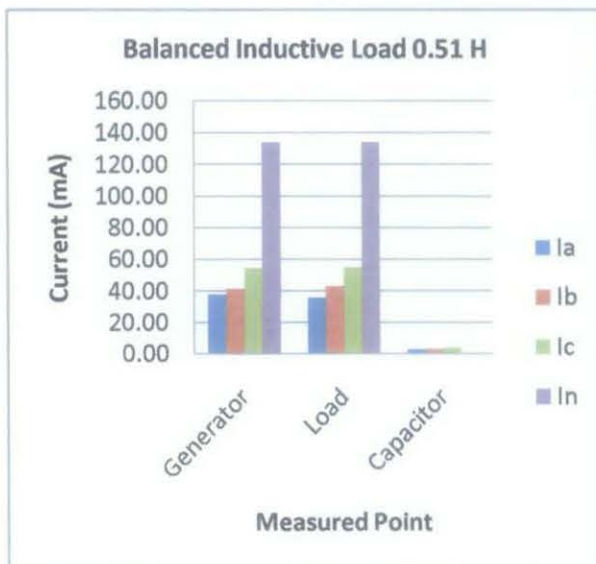

Figure 112: 3rd harmonic current measured at various points with balanced inductive load 0.51 H

nductive Load 0.76 H Capacitor 0.66 uF

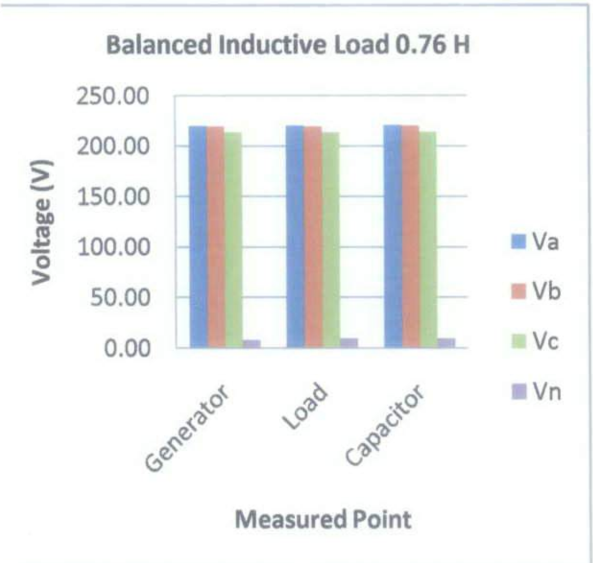

Figure 113: Fundamental voltage measured at various points with balanced inductive load 0.76 H

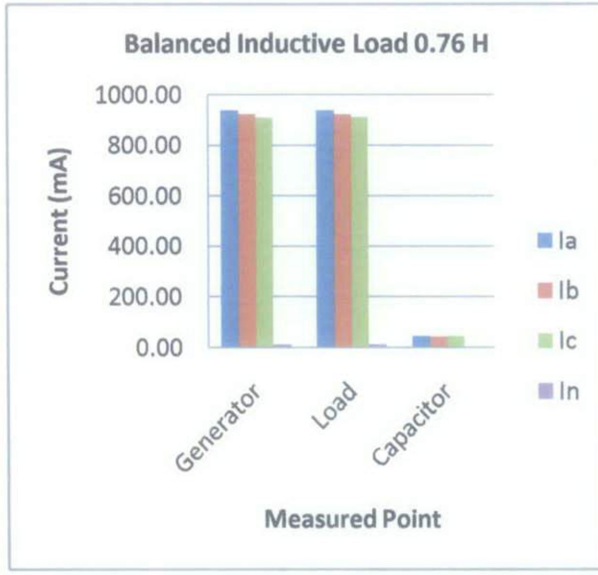

Figure 114: Fundamental current measured at various points with balanced inductive load 0.76 H

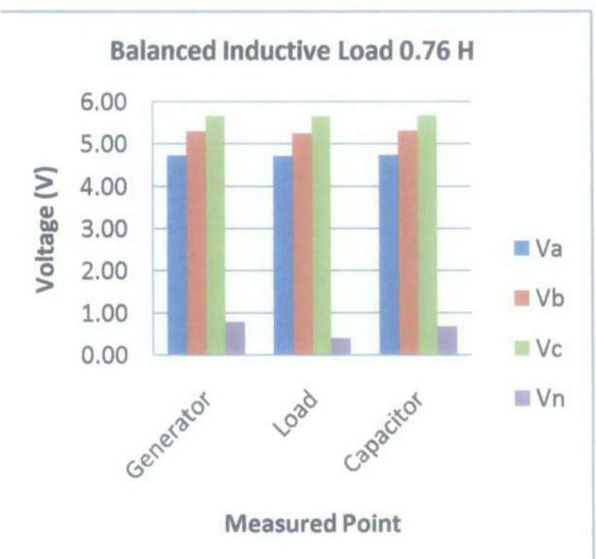

Figure 115: 3rd harmonic voltage measured at various points with balanced inductive load 0.76 H

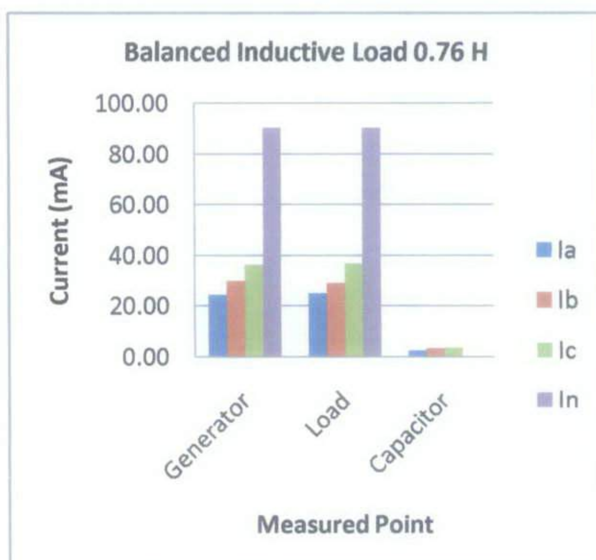

Figure 116: 3rd harmonic current measured at various points with balanced inductive load 0.76 H

nductive Load 1.02 H Capacitor 0.66 uF

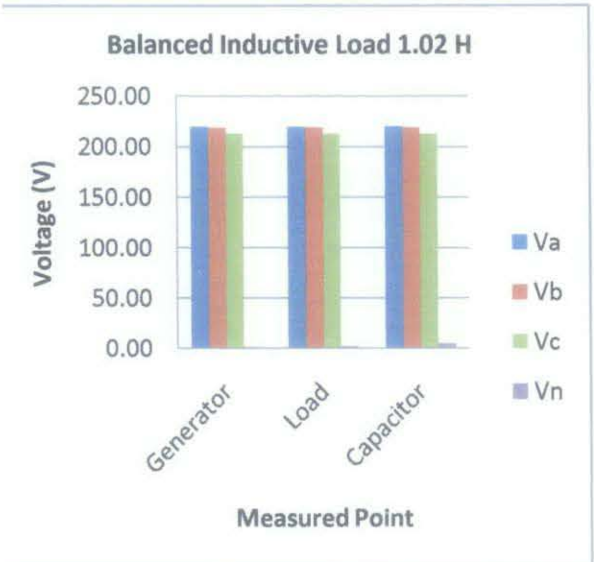

Figure 117: Fundamental voltage measured at various points with balanced inductive load 1.02 H

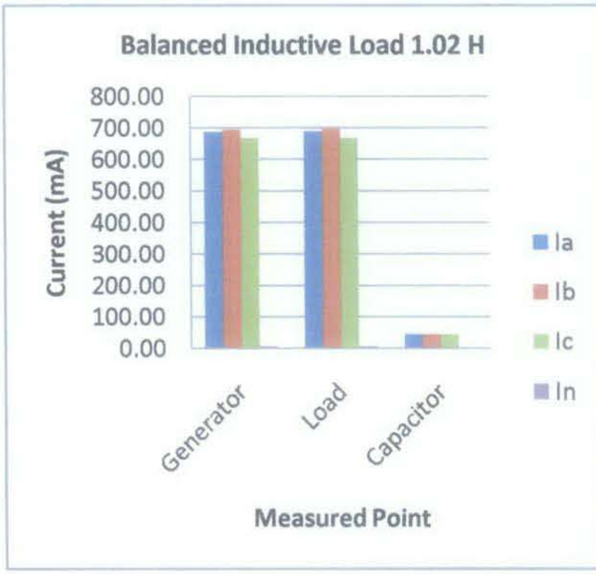

Figure 118: Fundamental current measured at various points with balanced inductive load 1.02 H

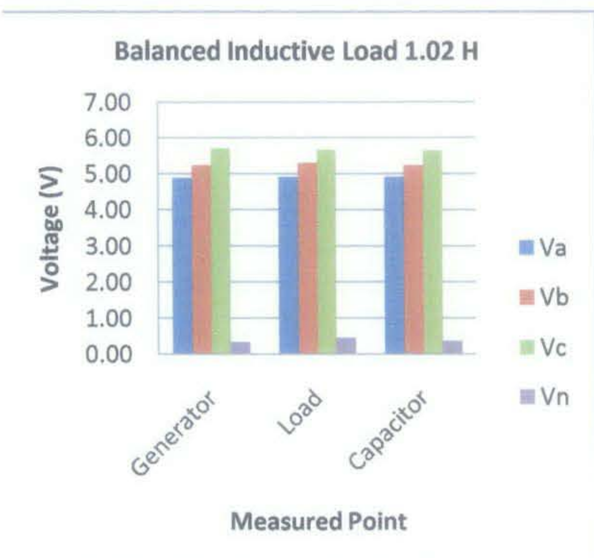

Figure 119: 3rd harmonic voltage measured at various points with balanced inductive load 1.02 H

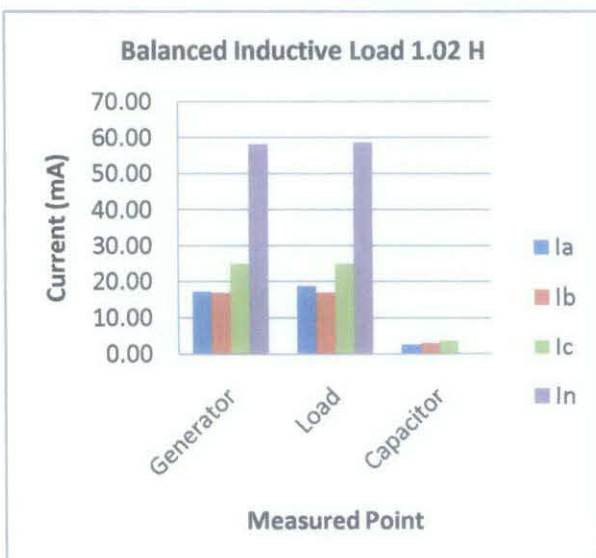

Figure 120: 3rd harmonic current measured at various points with balanced inductive load 1.02 H

nductive Load 1.53 H Capacitor 0.66 uF

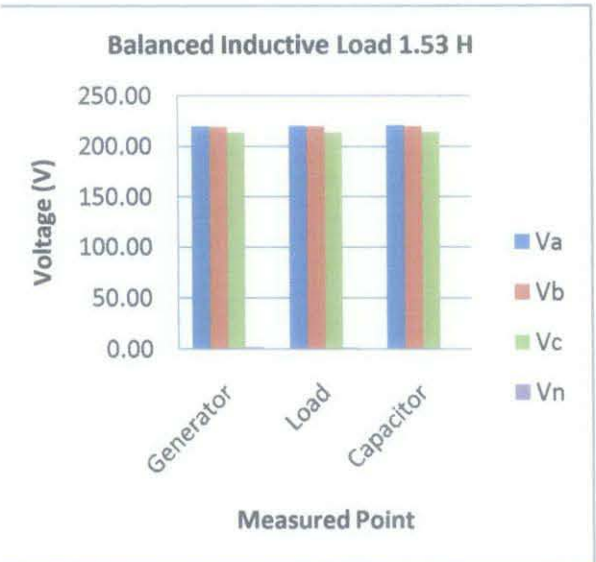

Figure 121: Fundamental voltage measured at various points with balanced inductive load 1.53 H

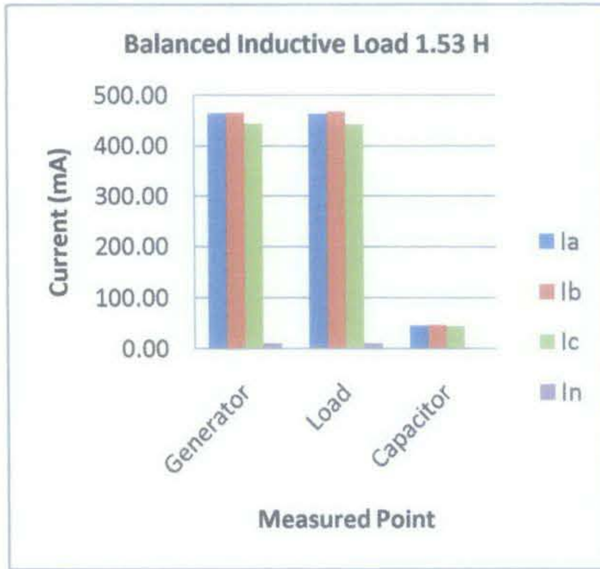

Figure 122: Fundamental current measured at various points with balanced inductive load 1.53 H

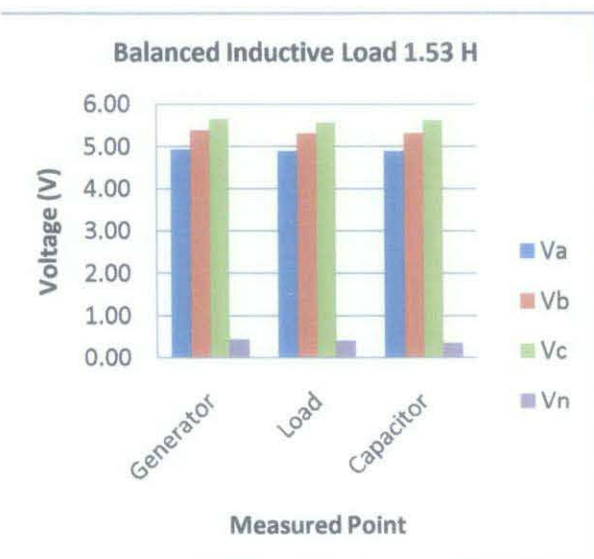

Figure 123: 3rd harmonic voltage measured at various points with balanced inductive load 1.53 H

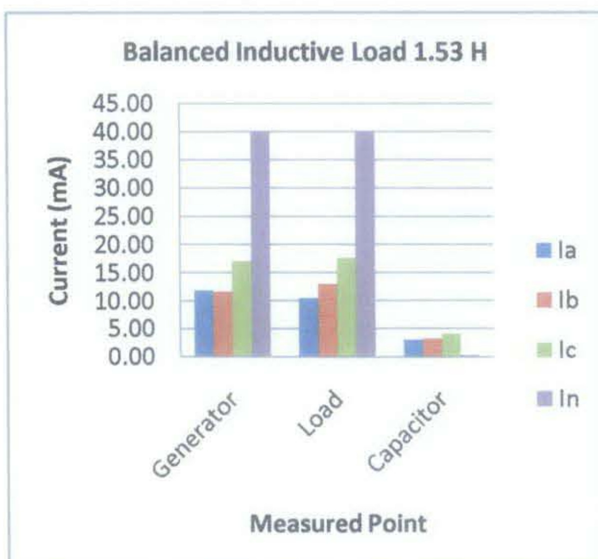

Figure 124: 3rd harmonic current measured at various points with balanced inductive load 1.53 H

nductive Load 0.38 H Capacitor 1.33 uF

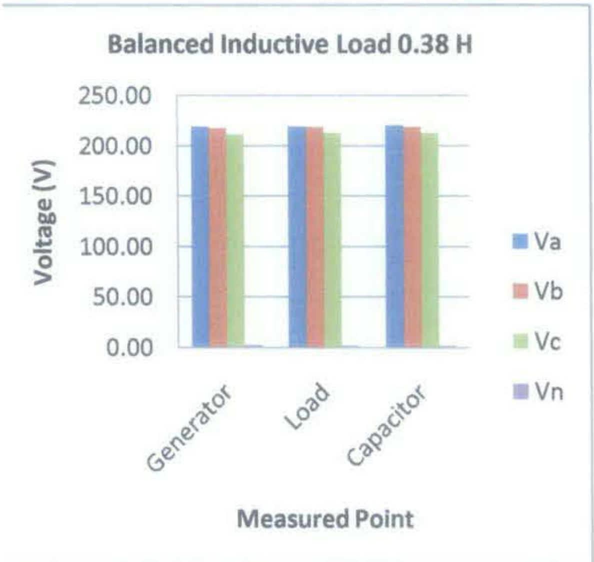

Figure 125: Fundamental voltage measured at various points with balanced inductive load 0.38 H

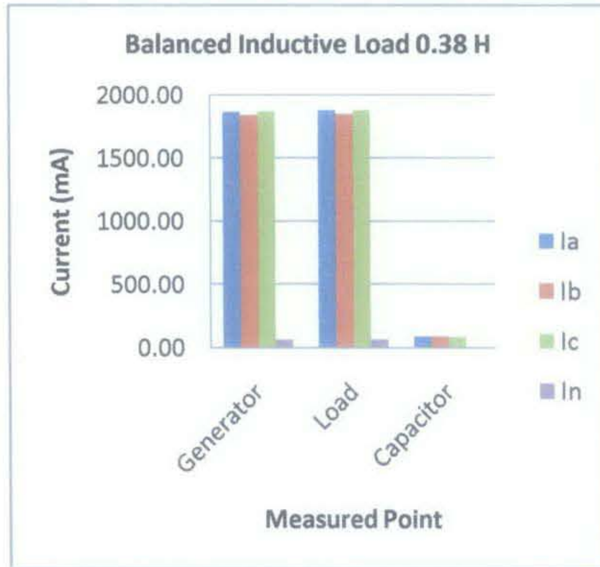

Figure 126: Fundamental current measured at various points with balanced inductive load 0.38 H

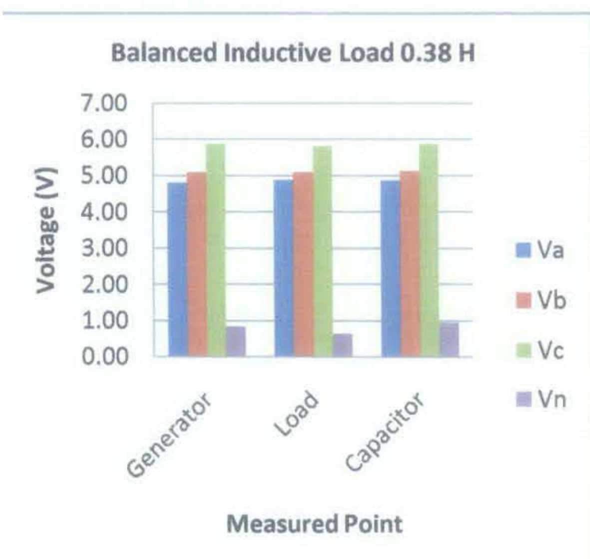

Figure 127: 3rd harmonic voltage measured at various points with balanced inductive load 0.38 H

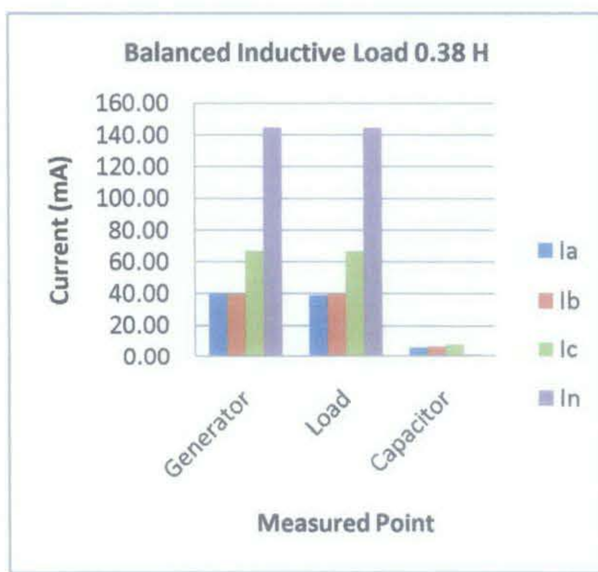

Figure 128: 3rd harmonic current measured at various points with balanced inductive load 0.38 H

nductive Load 0.51 H Capacitor 1.33 uF

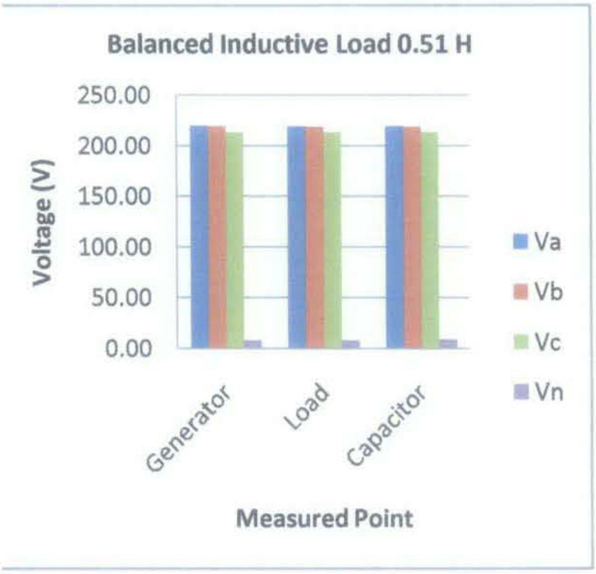

Figure 129: Fundamental voltage measured at various points with balanced inductive load 0.51 H

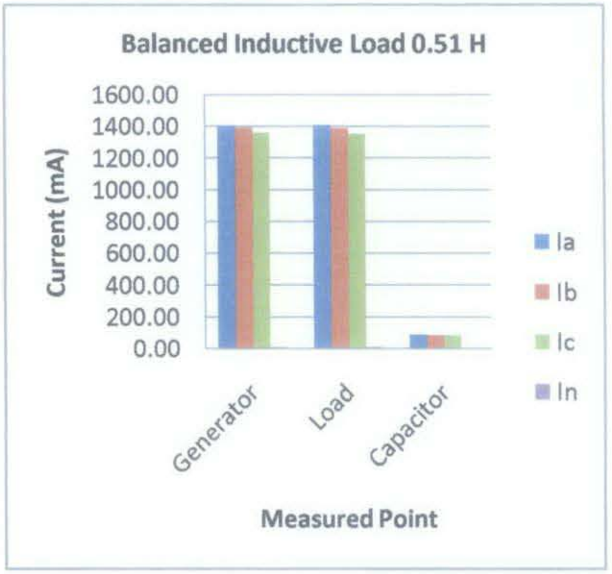

Figure 130: Fundamental current measured at various points with balanced inductive load 0.51 H

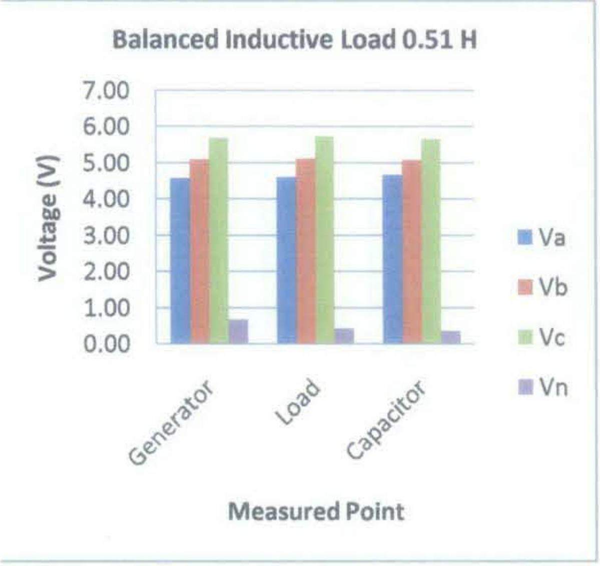

Figure 131: 3rd harmonic voltage measured at various points with balanced inductive load 0.51 H

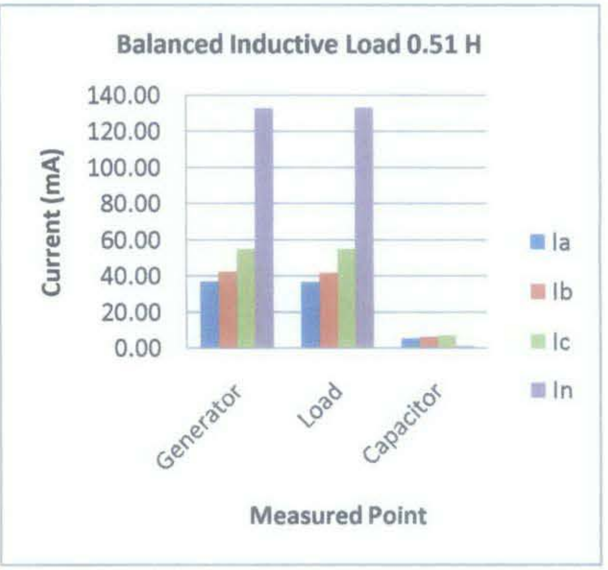

Figure 132: 3rd harmonic current measured at various points with balanced inductive load 0.51 H

nductive Load 0.76 H Capacitor 1.33 uF

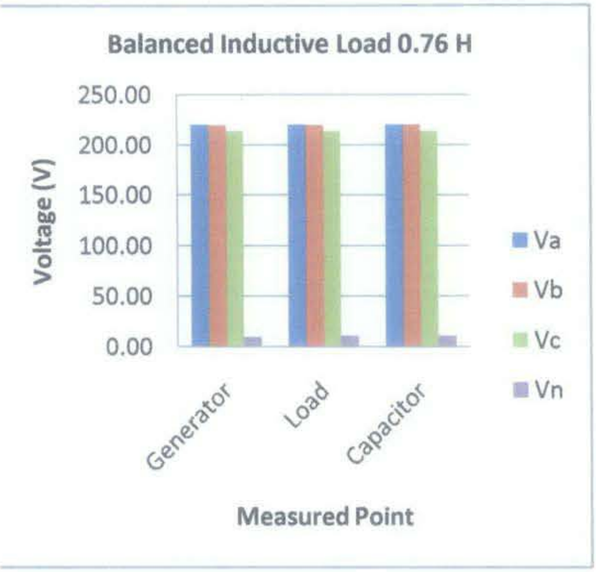

Figure 133: Fundamental voltage measured at various points with balanced inductive load 0.76 H

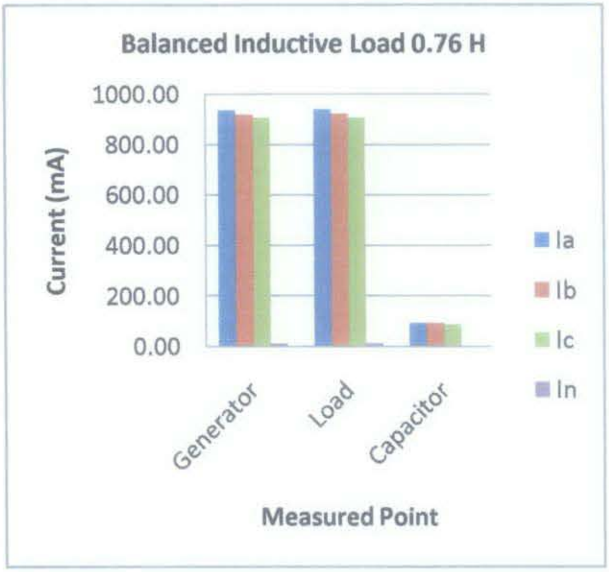

Figure 134: Fundamental current measured at various points with balanced inductive load 0.76 H

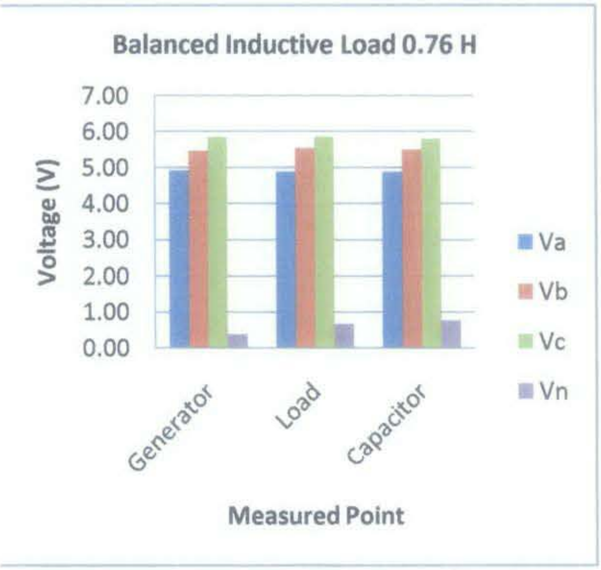

Figure 135: 3rd harmonic voltage measured at various points with balanced inductive load 0.76 H

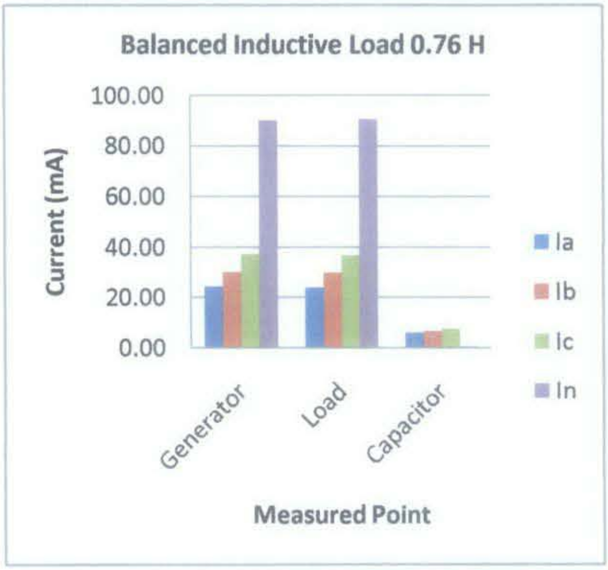

Figure 136: 3rd harmonic current measured at various points with balanced inductive load 0.76 H

nductive Load 1.02 H Capacitor 1.33 uF

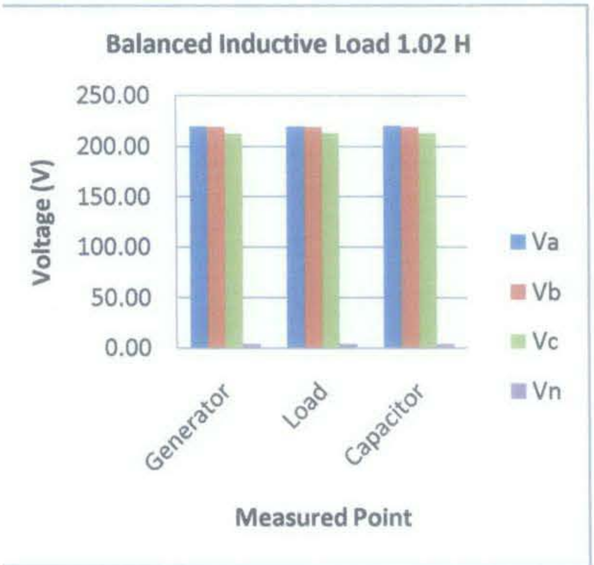

Figure 137: Fundamental voltage measured at various points with balanced inductive load 1.02 H

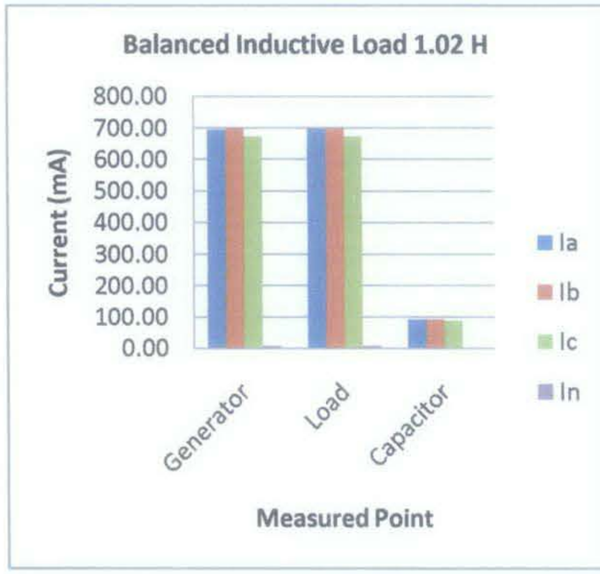

Figure 138: Fundamental current measured at various points with balanced inductive load 1.02 H

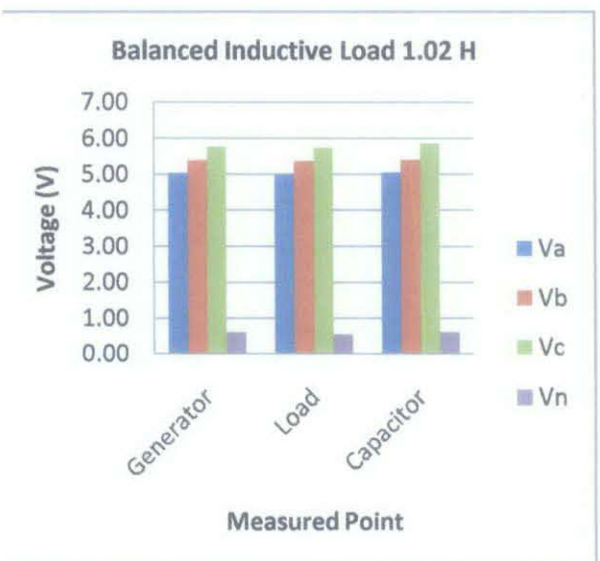

Figure 139: 3rd harmonic voltage measured at various points with balanced inductive load 1.02 H

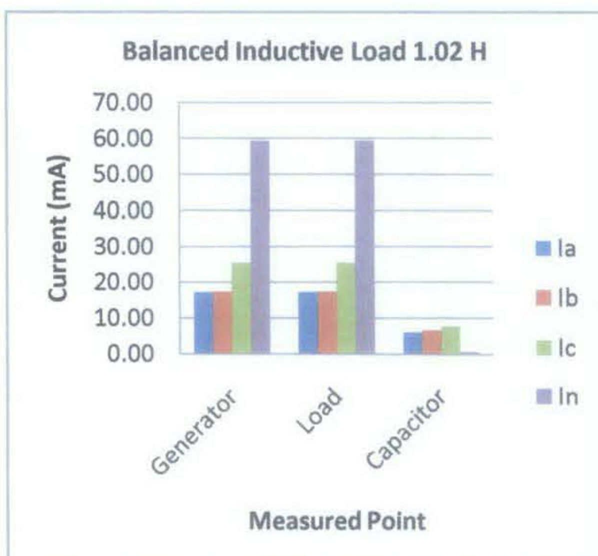

Figure 140: 3rd harmonic current measured at various points with balanced inductive load 1.02 H

nductive Load 1.53 H Capacitor 1.33 uF

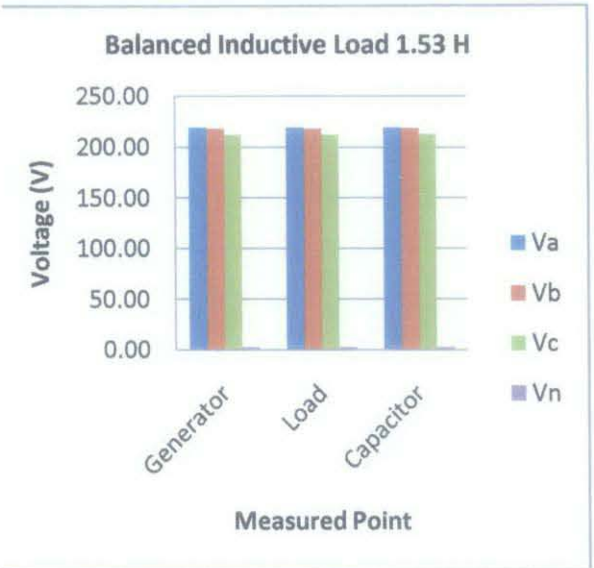

Figure 141: Fundamental voltage measured at various points with balanced inductive load 1.53 H

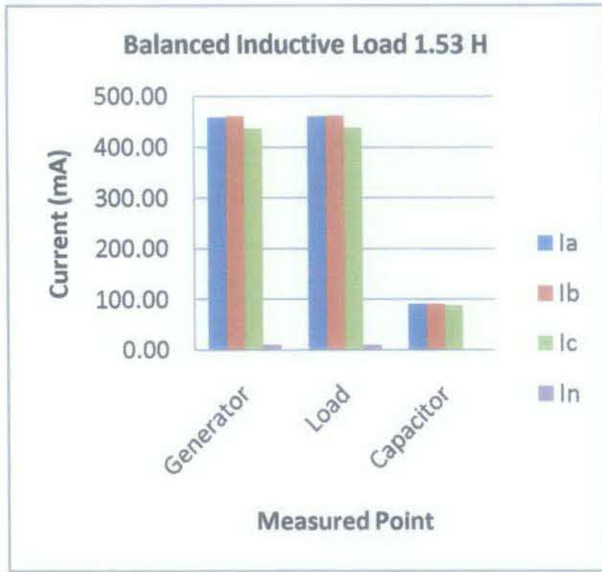

Figure 142: Fundamental current measured at various points with balanced inductive load 1.53 H

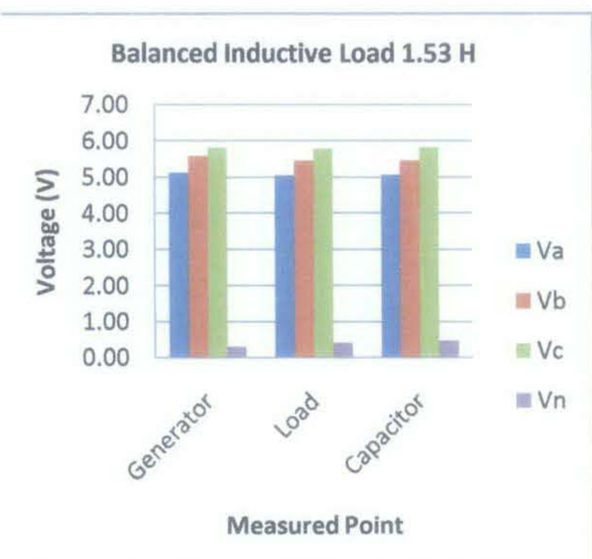

Figure 143: 3rd harmonic voltage measured at various points with balanced inductive load 1.53 H

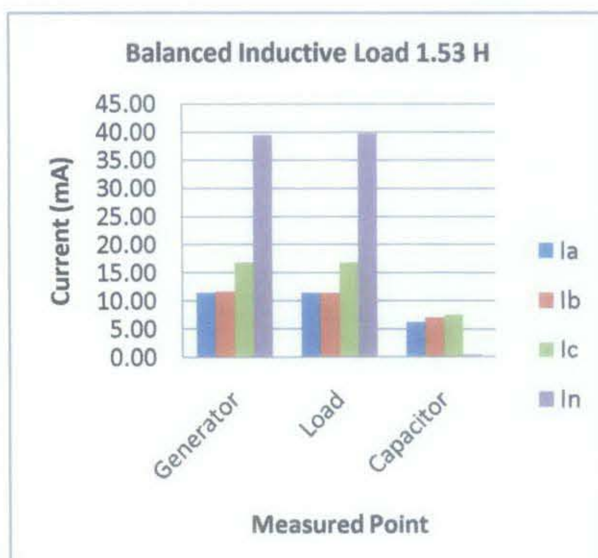

Figure 144: 3rd harmonic current measured at various points with balanced inductive load 1.53 H

nductive Load 0.38 H Capacitor 2.56 uF

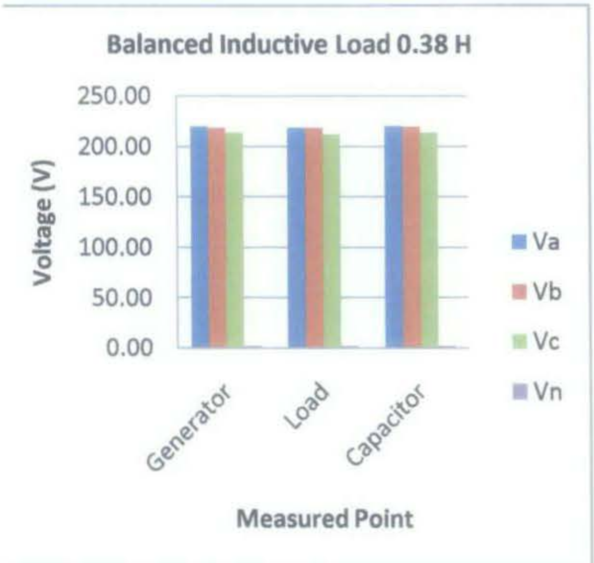

Figure 145: Fundamental voltage measured at various points with balanced inductive load 0.38 H

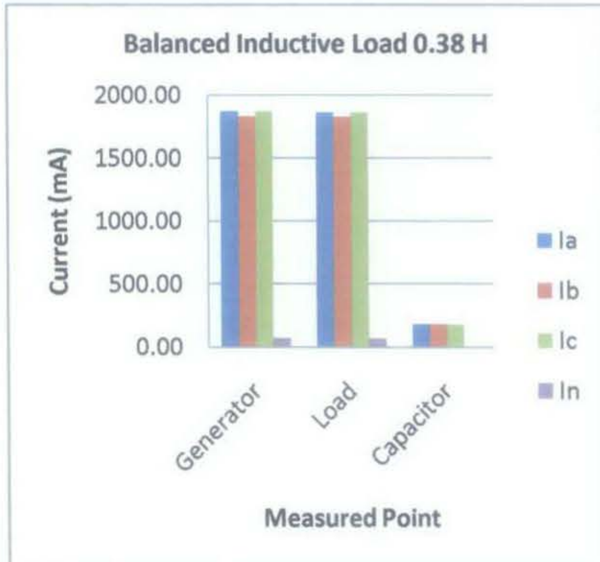

Figure 146: Fundamental current measured at various points with balanced inductive load 0.38 H

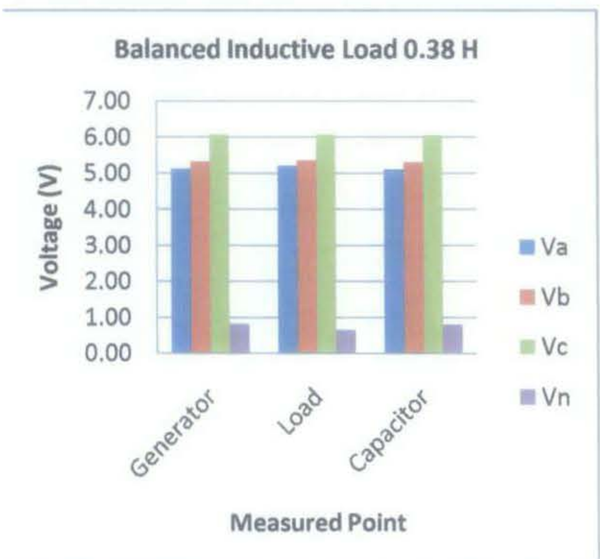

Figure 147: 3rd harmonic voltage measured at various points with balanced inductive load 0.38 H

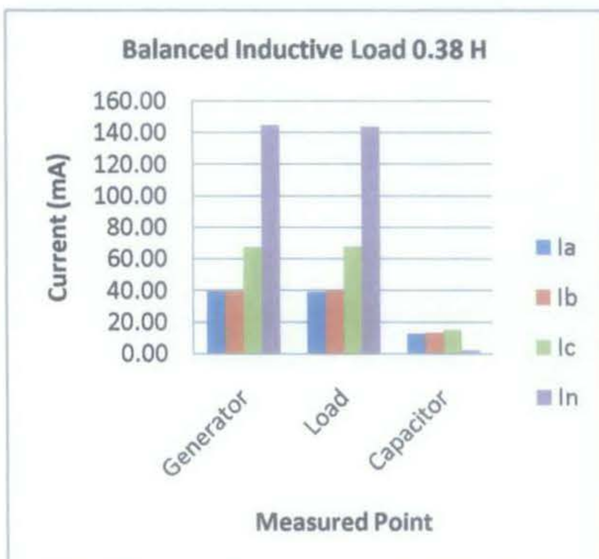

Figure 148: 3rd harmonic current measured at various points with balanced inductive load 0.38 H

nductive Load 0.51 H Capacitor 2.56 uF

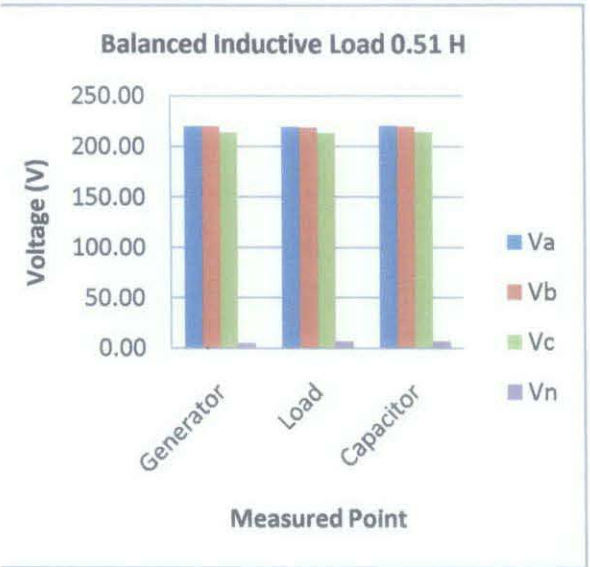

Figure 149: Fundamental voltage measured at various points with balanced inductive load 0.51 H

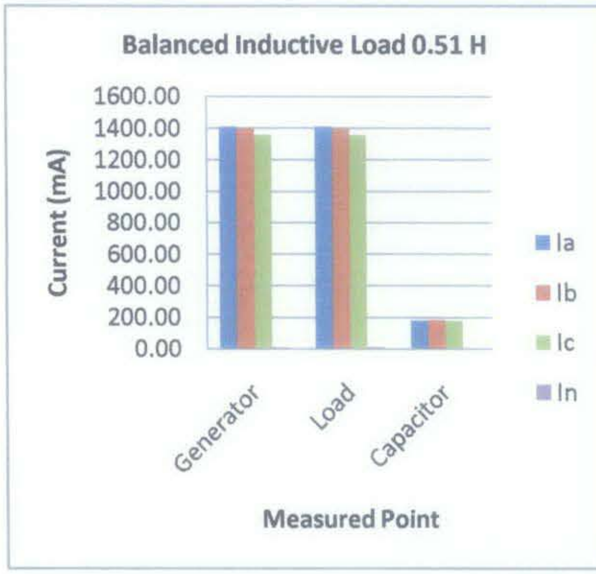

Figure 150: Fundamental current measured at various points with balanced inductive load 0.51 H

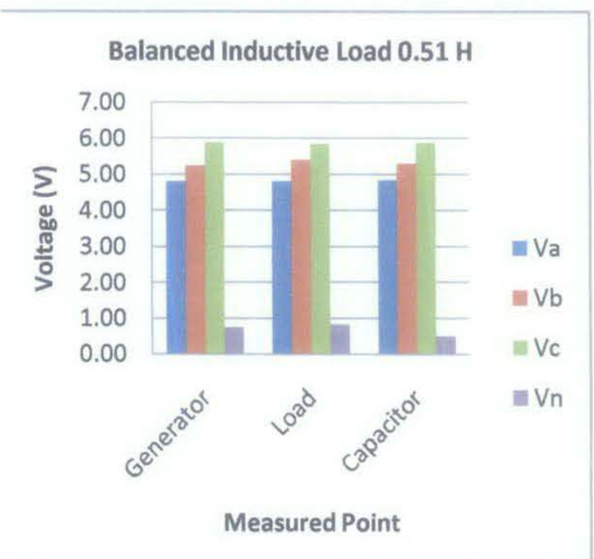

Figure 151: 3rd harmonic voltage measured at various points with balanced inductive load 0.51 H

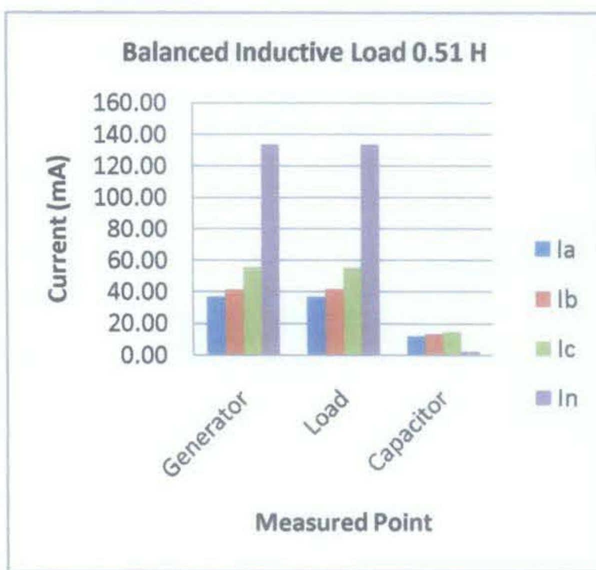

Figure 152: 3rd harmonic current measured at various points with balanced inductive load 0.51 H

nductive Load 0.76 H Capacitor 2.56 uF

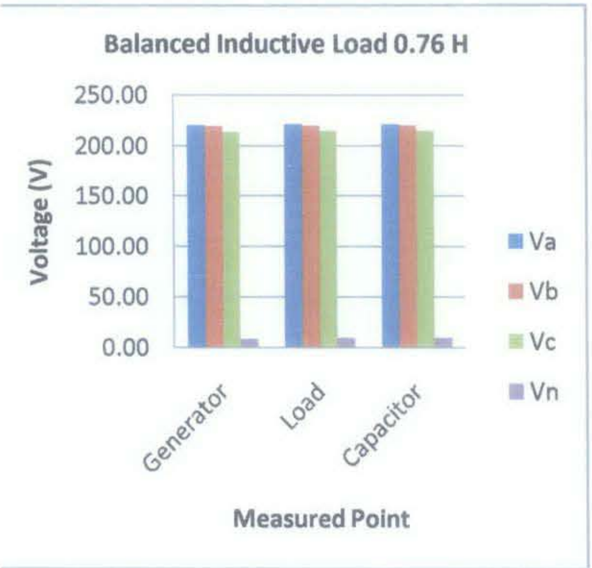

Figure 153: Fundamental voltage measured at various points with balanced inductive load 0.76 H

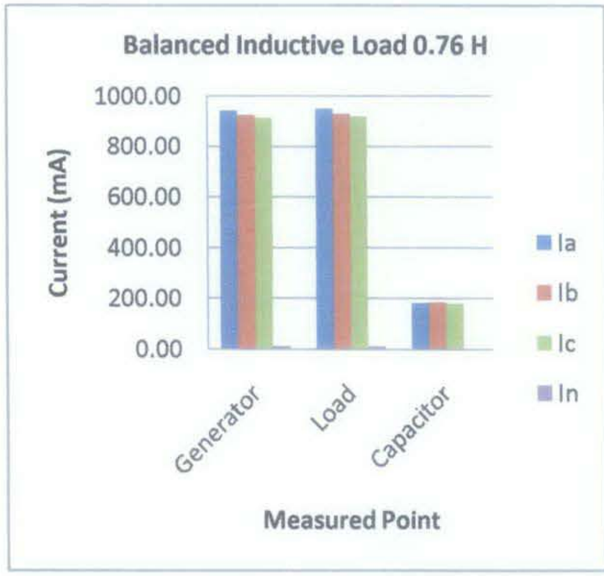

Figure 154: Fundamental current measured at various points with balanced inductive load 0.76 H

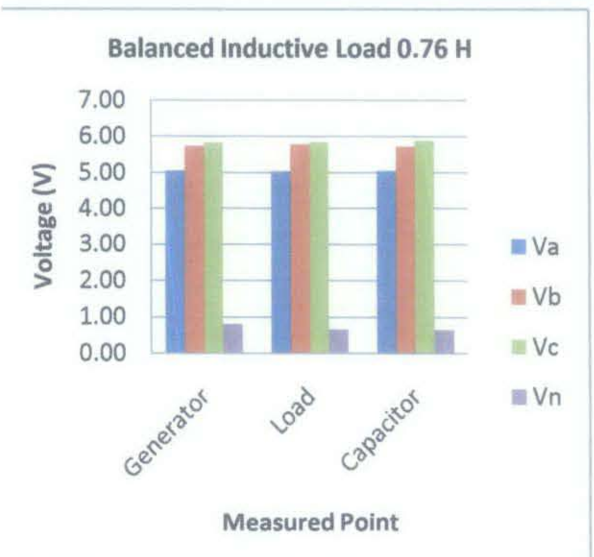

Figure 155: 3rd harmonic voltage measured at various points with balanced inductive load 0.76 H

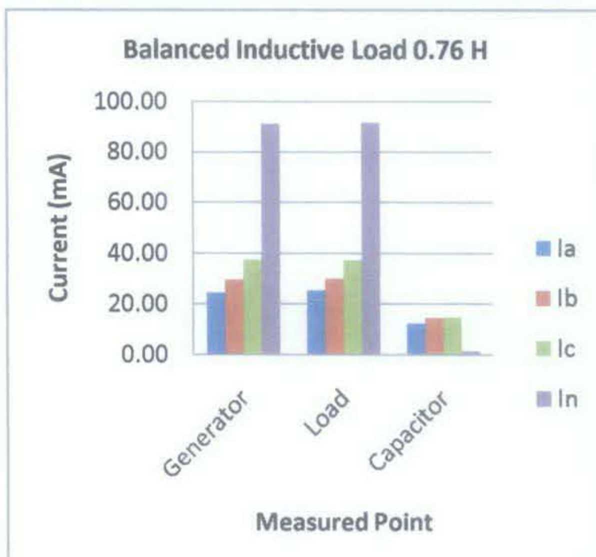

Figure 156: 3rd harmonic current measured at various points with balanced inductive load 0.76 H

nductive Load 1.02 H Capacitor 2.56 uF

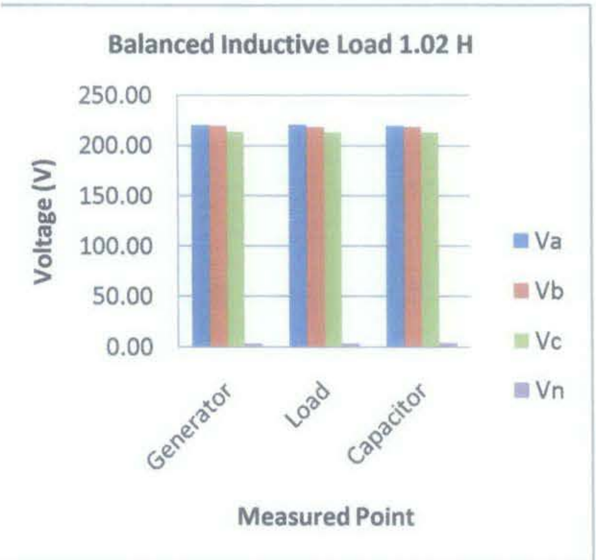

Figure 157: Fundamental voltage measured at various points with balanced inductive load 1.02 H

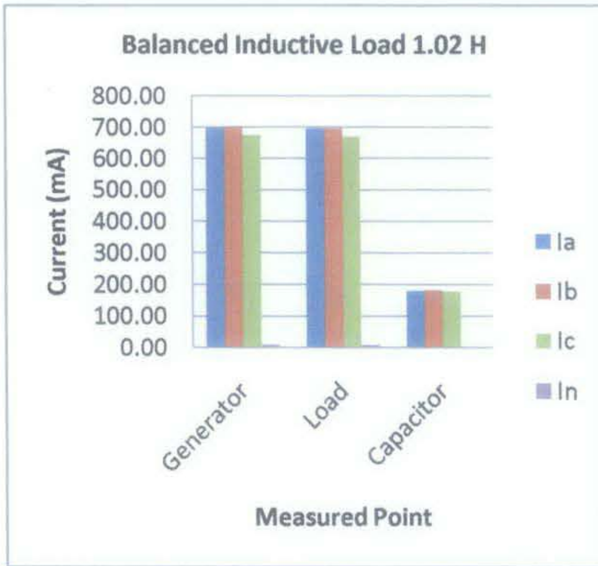

Figure 158: Fundamental current measured at various points with balanced inductive load 1.02 H

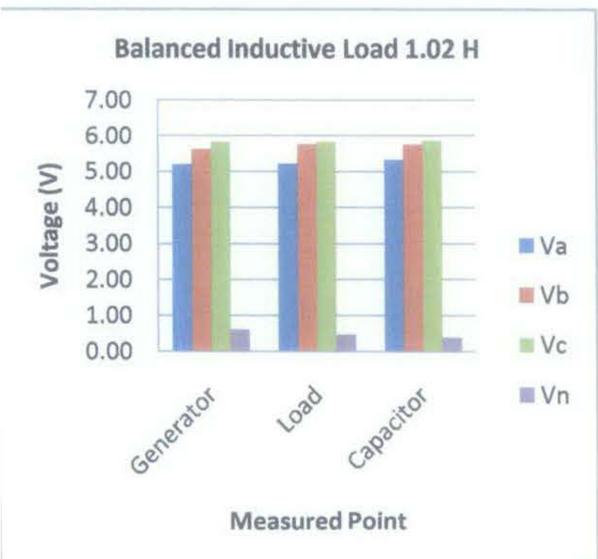

Figure 159: 3rd harmonic voltage measured at various points with balanced inductive load 1.02 H

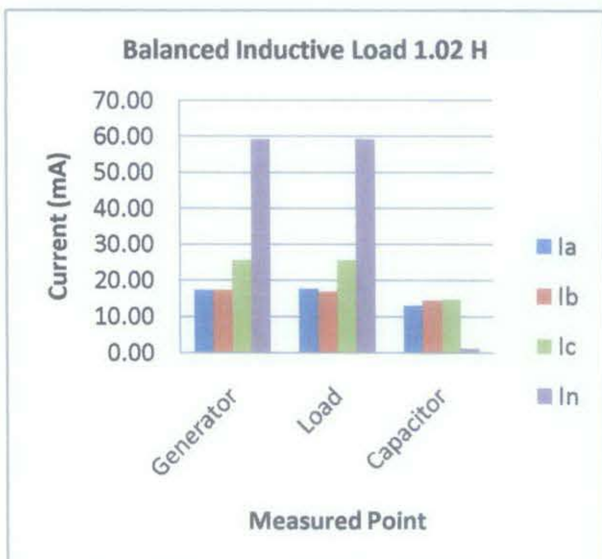

Figure 160: 3rd harmonic current measured at various points with balanced inductive load 1.02 H

nductive Load 1.53 H Capacitor 2.56 uF

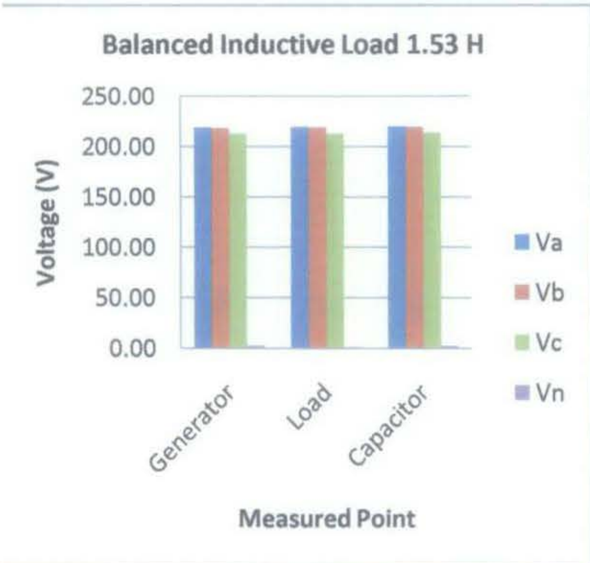

Figure 161: Fundamental voltage measured at various points with balanced inductive load 1.53 H

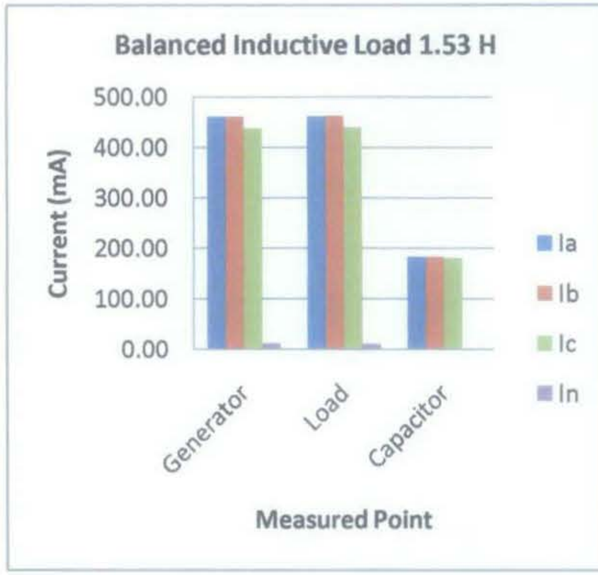

Figure 162: Fundamental current measured at various points with balanced inductive load 1.53 H

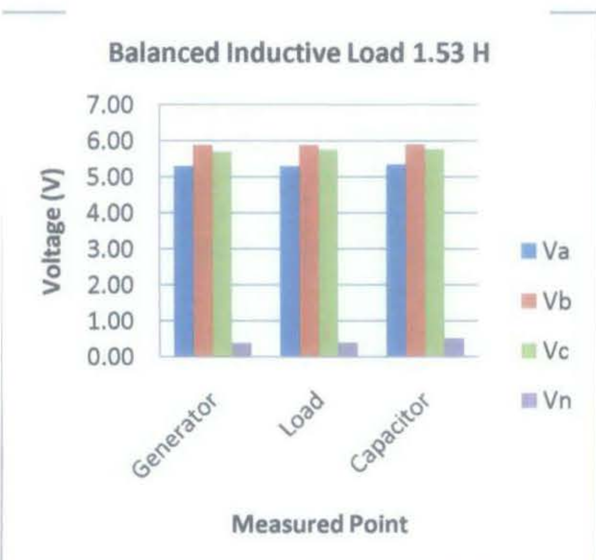

Figure 163: 3[rd] harmonic voltage measured at various points with balanced inductive load 1.53 H

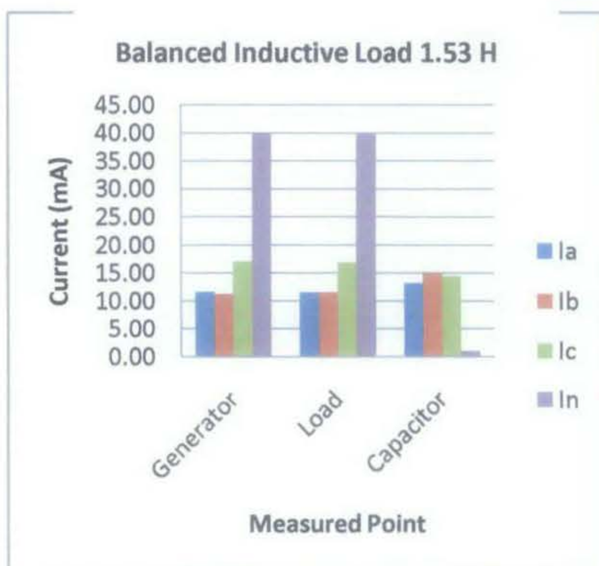

Figure 164: 3[rd] harmonic current measured at various points with balanced inductive load 1.53 H